Modern (Inter)Row hoes
The Swiss Army Knife of Mechanical Weeders.
A Comprehensive Guide

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The BHU Future Farming Centre

Permanent Agriculture and Horticulture Science and Extension

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Live, like you'll die tomorrow;
Farm, like you'll live for ever.

Dedication

This report is dedicated to Tim Chamberlain who trusted and employed me over many years to develop a wide range of weeding machinery for Harts Creek Farm.

About the author

Dr Charles 'Merf' Merfield MSRNZ is a world leading expert in physical weeding with over 30 years experience, including practical on-farm use, machinery design, and research. He has worked with nearly every kind of mechanical weeder in vegetable and arable cropping systems. This started in the late 1980s with a brush hoe at sunnyfields.co.uk, where the slight ridging effect of the crop protection tunnels eventually led him to re-invent the mini-ridger. The majority of his mechanical weeding development work took place at hartscreekfarm.co.nz. This included using the original Buddingh Weeder Co finger weeders and basket weeder, the latter of which he then re-engineered, as well as optimising the design of naturally aspirated flame weeders. He has driven a diverse range of old-school tool carriers with mid-mount weeding systems including Farmall, Fiat and Allis Chalmers G. Many hours of trials and tribulations were spent using multiple makes of interrow hoes, culminating in designing from first principles, as well as building, a high clearance row hoe for sweetcorn in 2013. His time at Harts Creek Farm also involved using some of the first RTK GPS tractor autosteer in New Zealand which was game changing for interrow hoeing, as well as using the first computer vision systems which were more of challenge. He has also optimised the design of the rigid tool clamp physicalweeding.com/merfclamp and his pride and joy is the 4 Wheel Hoe www.physicalweeding.com/fourwheelhoe a pedestrian row hoe for small scale market gardens. He also provides one-to-one consulting, advice to farmers, growers and research, workshops and fieldays for industry, on all aspects of non-chemical and integrated weed management, as well as all aspects of sustainable farming.

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1. Summary - key points

Introduction

- Weed management in cropping systems is changing from domination by herbicides to Integrated Weed Management (IWM) with mechanical weeding playing an ever increasing role.
- This report is aimed at commercial farmers and growers of annual crops wanting or needing to reduce or eliminate herbicides by shifting to mechanical weeding. It is also for organic farmers and growers, and those already using interrow hoes wanting to improve their understanding.
- This report is also European centric for multiple reasons, the authors experience, that Europe re-invented its mechanical weeders post the 1960s resulting in it developing many new and innovative approaches that are increasingly being taken up further afield.
- Interrow hoeing dates in the Western world to the 1700s when Jethro Tull developed the seed drill to allow horse hoeing.
- Not only has mechanical weeding advanced considerably over the following centuries, in the last three decades it has moved from simple mechanical approaches to highly sophisticated computer controlled systems.
- Concerns are raised about the energy use and negative impacts on soil health from mechanical weeding. Mechanical weeder use less, to far less energy than herbicides. The impacts on soil health are shared with herbicides and are primarily due to killing weeds which reduces plant diversity and biomass, rather than direct negative impacts.
- Without organic farming prohibiting synthetic herbicides very little of the current mechanical weeding technology would exist. A debt of gratitude is owed.

Row hoes are the finale not the start of non-chemical and integrated weed management

- While modern row hoes can achieve exceptional in-crop weed management, without a whole-of-farm system / integrated approach to weed management failure is assured. Admoniti estis — You have been warned.

Where row hoes fit in the mechanical weeding pantheon

- There are now a diverse range of mechanical weeders. These are primarily divided into contiguous weeders which weed the whole field surface and incontiguous weeders that separately weed the interrow and intrarow.
- As what used to be called interrow hoes now also weed the intrarow, i.e., the crop row, the name has been changed to row hoe.
- There are two intrarow weeder approaches. High tech / discriminatory which mostly use computer vision systems and low tech / non-discriminatory that weed crop and weeds alike and rely on the crop being more resistant to the weeder than the weeds.

A comprehensive guide to row hoes

- There are a range of specialist terms used in row hoeing but without agreed definitions, so key terms are defined.
- A primary requirement of row hoeing is that the planter and drill rows, both the number and spacing, exactly match the crop gaps in the weeder.
- Tractor size and power is based on the need to lift the weeder on the three point linkage, not draft which is small.
- Soil, type, texture, stonyness and moisture along with weather conditions can all significantly impact mechanical weeding, just the same as for tillage, and thus require constant monitoring to ensure effectiveness.

- Mechanical weeding and herbicides are not mutually exclusive, indeed there is much to gained by their informed integration.
- Suitable weather conditions for mechanical weeding often contrast to the weather required for herbicide spraying, so when both options are available this considerably widens the weeding weather window.
- In mechanical weeding it is the weed, not the crop growth stage, that mostly determines timing of weeding, and getting the timing of weeding right is critical.
- The limit to what can be row hoed is very high density vegetables, e.g., baby salads, though new weeders for even these crops are being developed.

Modular, parallelogram, weeding units — a 'Swiss army knife' weeding platform

- There is a considerable amount of technical details in the design of row hoes.
- Modularisation allows row hoes designs to be highly flexible and their size is only limited by machinery strength and practical in-field considerations.
- The toolbar connects the tractor to the modular parallelogram weeding units.
- The parallelogram allows the weeding frame to maintain the correct height above the soil and parallel with the ground along its full length.
- The design of weeding units is really important to the overall effectiveness of a row hoe.
- Achieving the correct downforce on the weeding frame has lead to pneumatic and hydraulic systems that now permit advanced features such as section control
- Modern, modular row hoes are less of a weeder themselves, they are more of a platform for a diverse range of weeding tools that are mixed and matched to the crop, weed, soil and weather conditions — hence why they are the 'Swiss army knife of mechanical weeders'.

Weeding frames

- A well designed weeding frame that allows a range of types and number of weeding tools to be attached and easily adjusted is an important component of a good row hoe.
- Weeding frame design needs to be matched to crop type and row spacing to ensure all the required weeding tools can fit onto the frame.
- There are two main weeding frame design approaches: end connected and center connected. Center connected is clearly now the preferred and more flexible approach.
- The width of weeding frames / the number of weeding units is driven by crop row width and configuration, i.e., continual rows in arable and with wheelings and beds in vegetables.
- To maximise the efficacy of row hoes, the maximum amount of the field surface needs to be interrow and the minimum in the intrarow., i.e., the width of the interrow needs to be maximised and intrarow minimised.

Weeding tools

- Understanding the many different types of weeding tool and the design specifics of each is, essential for choosing the correct tool for a weeding job and ensuring their most effective use.
- Most weeding tools are based on horizontal steel blades that slice through the soil.
- Horizontal blades are subdivided into a three main types based on their shape: L T and A blade hoes along with ducksfoot / goose foot points.
- While they may appear superficially simple, there is considerable complexity in horizontal hoe blade designs, including multiple blades angles.
- L and T hoes are designed to weed next to the crop row. L hoes are the standard design, while T hoes are less common they have a number of advantages and are underutilised.

- A blade hoes along with ducksfoot / goosefoot points, aka sweeps, are designed to weed down the center of the interrow. The key difference between them is the pitch angle and therefore how much they dig into the soil and move soil sideways towards the crop row.
- Many weeding tools are used too deep, they should be targeting the weeds' hypocotyl and thus should only be deep enough in the soil so they can effectively cut the weeds.
- There are a range of non-blade weeding tools including, rotating spider hoes, mini-tine weeders and crumblers, designed to further break up soil and dislodge it from weed roots.
- Most row hoes (and other mechanical weeders) cannot work in high residues but can cope with low to medium amounts of residue. There are specific row hoe designs for high residue systems.
- Electrical interrow weeders have the potential to address issues such as weeding high residue systems, and killing larger weeds and weeding when the soil is too wet for mechanical weeding.

Weeding tool legs and springs

- The tool leg connects the weeding tool to the weeding frame. These are also surprisingly technical. Good design is key to their efficacy and ease of adjustment.
- There are both sprung and rigid legs.

Weeding frame - weeding tool clamps

- It is surprising how the basic mechanical task of clamping two pieces of steel at right angles - the weeding tool leg to the weeding frame bar - can be done so badly, and to be done really well, requires excellent design.
- Vertical and horizontal adjustment should be locked individually.
- e-spring clamps inherently have independent axis locking.

Intrarow weeders - discriminatory and non-discriminatory

- Intrarow weeding tools are divided into two types: 1. discriminatory / high tech and 2. non-discriminatory / low tech.
- Discriminatory weeder systems are mostly computer vision system based, they are therefore complex and often built as a single machine, with interrow weeding systems integrated into them. They are therefore outside the scope of this report.
- Non-discriminatory weeders are simple mechanical (low-tech) tools with a diverse range of highly effective weeding actions.
- There are now sufficient types of non-discriminatory intrarow weeders that fit onto row hoes that exceptional whole-of-field weed management using only row hoes is now a reality.
- Before buying into the cost and complexity of discriminatory weeders, it is strongly recommended that non-discriminatory weeders on row hoes should be tried first until it is proven they can't achieve good enough weed management, and thus a discriminatory weeder is justified.
- The main intrarow weeders are in order of importance / common use: finger weeders, mini-ridgers, concave disks and ridgers, torsion weeders and rotating vertical wire weeders.
- Most of the intrarow weeders are highly complimentary and will achieve the best overall weed management when used in combination / sequences.

Crop protection systems

- Small crop plants are at risk of being buried and killed under soil flowing off weeding tools.
- Crop protection systems keep soil out of the intrarow, protecting small crop plants, and larger vegetables from soil contamination.

The critical importance of accurate and precise setup of drills, planters and row hoes

- It is essential that all row-equipment: drill, planter and row hoe are set up to exactly the same spacings.
- With the exceptional accuracy of computer guidance and many manual steering systems all machines need to be setup with high levels of accuracy and precision.
- Using jigs, marker bars, and similar techniques helps achieve the require accuracy and precision with the least amount of in-field setup.
- Once in-field, final tweaking of setup will be required due to differences in soil and crop.
- Once operating, constant vigilance is the watchword of the row hoer.

Guidance systems

- Computer guidance systems based on either RTK GPS or computer vision systems have revolutionised interrow hoeing.
- Nearly all guidance systems are now vision systems indicating they have an overall advantage.
- Coupling the now common RKT GPS tractor autosteer with vision guidance on the row hoe is a dream-combination.
- There are both old and new low-tech guidance systems such as sensor wands that are still good options in the right situation.
- Manual guidance is still viable and is the common approach on small farms.

Alternative interrow hoe designs - a very brief guide

- While for many years the different interrow designs were mostly equals, modern, especially 2nd Generation row hoes are now the clear winners in the row-crop weeding race.
- Other designs, such as the rotary tiller, brush hoe, basket weeder and vertical axis rotary weeder are now niche machines.
- However, there are soil and weather situations where brush hoes and vertical axis weeder can achieve good weed management when row hoes are stuck in the shed.
- The basket weeder retains its niche due to low cost and mechanical simplicity.
- There is a small but growing range of simple designs of interrow hoes for arable crops.

Conclusions

- Interrow hoes have come a very long way from Jethro Tull's initial conceptualisation!
- Modular, parallelogram row hoes, with both interrow and intrarow weeding tools are now the dominant form of crop row weeder.
- The degree of sophistication of Second Generation row hoes is astonishing compared with their predecessors.
- Computer guidance systems, particularly camera based vision systems, are now a mature and highly effective technology.
- When coupled with RTK GSP tractor autosteer the tractor driver has changed to become a machinery supervisor, ensuring optimal machine performance.
- With row hoe widths now reaching 30 meters / yards and forward speeds only limited by tractor and weeder work rates, weed control equivalent to herbicides are now possible.
- With the ever growing challenges facing herbicides, in row-crops, modern row hoes are now a key component of Integrated Weed Management that will only increase in importance.

Happy weeding™

2. Introduction

2.1. Key points

- Weed management in cropping systems is changing from domination by herbicides to Integrated Weed Management (IWM) with mechanical weeding playing an ever increasing role.
- This report is aimed at commercial farmers and growers of annual crops wanting or needing to reduce or eliminate herbicides by shifting to mechanical weeding. It is also for organic farmers and growers, and those already using interrow hoes wanting to improve their understanding.
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- Concerns are raised about the energy use and negative impacts on soil health from mechanical weeding. Mechanical weeder use less, to far less energy than herbicides. The impacts on soil health are shared with herbicides and are primarily due to killing weeds which reduces plant diversity and biomass, rather than direct negative impacts.
- Without organic farming prohibiting synthetic herbicides very little of the current mechanical weeding technology would exist. A debt of gratitude is owed.

2.2. The changing face of weed management

With the ever increasing challenges facing herbicides — principally herbicide resistance, very limited new chemistry, as well as legislative and consumer ‘resistance’ — plus the ongoing expansion of organic agriculture and agroecology, mechanical weeding is an increasingly important technology, to the point that in the last few years it has become mainstream. However, for those new to mechanical weeding the vast range of different types of machines can be daunting and confusing. This report therefore gives a comprehensive guide to what used to be called interrow hoes or row-cultivators, the main form of mechanical weeding for row-crops. It also has a bit of the history of interrow hoeing and how the modern ‘row hoe’ fits within the pantheon of mechanical weeders. What it is not is a comparison of machines from specific manufacturers, rather it aims to cover the design principles and practical usage issues of row hoes at a more generic level that applies to all manufactures’ machines.

2.3. Who this report is for?

This report is aimed at mainstream commercial farmers and growers of annual and biennial crops grown in rows who want, or have to, reduce or even eliminate the use of herbicides, through mechanical weeding. It is also for organic farmers and growers and others who are already using mechanical weeding and want to improve their knowledge of row hoes both machines and techniques. It also aims to be of value to scientists, extension agents and others involved in supporting farmers and growers in the transition away from herbicides. It assumes a good understanding of annual crop farming and growing systems.

2.4. Two continents separated by a common weed problem

This report is also mostly written from a European perspective but is aimed at a global audience. Firstly this is due to my personal experience being mostly of European weeding systems. It is further in part due to the divergence in the Western World of weed management between Europe and North America. N. American mechanical weeding is mostly a continuation from the pre-herbicide era. It is split between the large scale, broadacre row-crops such as maize and soybean, and intensive organic market garden vegetable systems. In the row-crops, large, very heavy duty interrow hoes with big sweeps dominate. While in market gardens (especially organic) a much wider range of weeding approaches, particularly pre-herbicide era tool carriers (such as the Allis-Chalmers Model G) with a range of weeding tools. In Europe the pre-herbicide era mechanical weeding slate appears to have mostly been wiped clean, very few old machines and designs are used. Weeders have been re-created afresh post the 1960s, such as spring tine weeders, brush hoes, and modular parallelogram hoes designed not just for wide spaced row-crops, but for both arable and vegetable crops. Thus in the Western World, Europe has seen more mechanical weeding innovation, while N. America has mostly been sticking to tried and tested pre-herbicide approaches.

The situation is reminiscent of George Bernard Shaw's quote "The United States and Great Britain are two countries separated by a common language". Despite having generally similar farming systems, climate and the same language, the two continents have in the last few decades gone down different mechanical weeding pathways, as well having diverged over most aspects of weed management and science. What is increasingly clear is that European row hoes, particularly 2nd Generation machines with computer guidance systems (see below), are increasingly making inroads into N. America, while the reverse is not true.

This separation is even greater between the West and East. There have been only a small number of visits by Western farmers, growers and scientists to the East, mainly Japan, to study their mechanical / organic weeding systems. These have revealed, to often surprised and chagrined Western visitors, a magnificent range of weeding machines and techniques, particularly for very intensive / small scale systems. This is saying nothing about wider Asia, South America, and Africa. There is likely much the mechanical weeding communities in different nations and regions could learn from each other were better collaborations established. In the mean time, online videos and machine translation are helping to bridge the divide (see section 8).

2.5. A bit of history — Jethro Tull and the seed drill

Mechanical weeding traces its origins in the Western World to one of the most famous names in agriculture: Jethro Tull[1] 1674 - 1741. Originally studying law and being called to the bar, he became more interested in agriculture and the application of scientific and experimental methods to farming. He is most famous for developing the seed drill. Before this, in Europe, seed was broadcast on the ground and then harrowed in. The same as today, broadcasting and harrowing (or rolling) seed results in uneven and often poor establishment as only a fraction of the seed is at the optimum depth. The seed drill was revolutionary in placing the majority of the seed at the optimal depth, and therefore achieving more even and higher emergence. What is less well known is Tull designed the seed drill, not so much to improve crop establishment but because "more especially as it admitted the use of the horse hoe" (Ransome, 1843, p. 100) Figure 1. By drilling the crop in rows it permitted the use of, what we would now call, an interrow hoe.

[1] https://en.wikipedia.org/wiki/Jethro_Tull_(agriculturist)

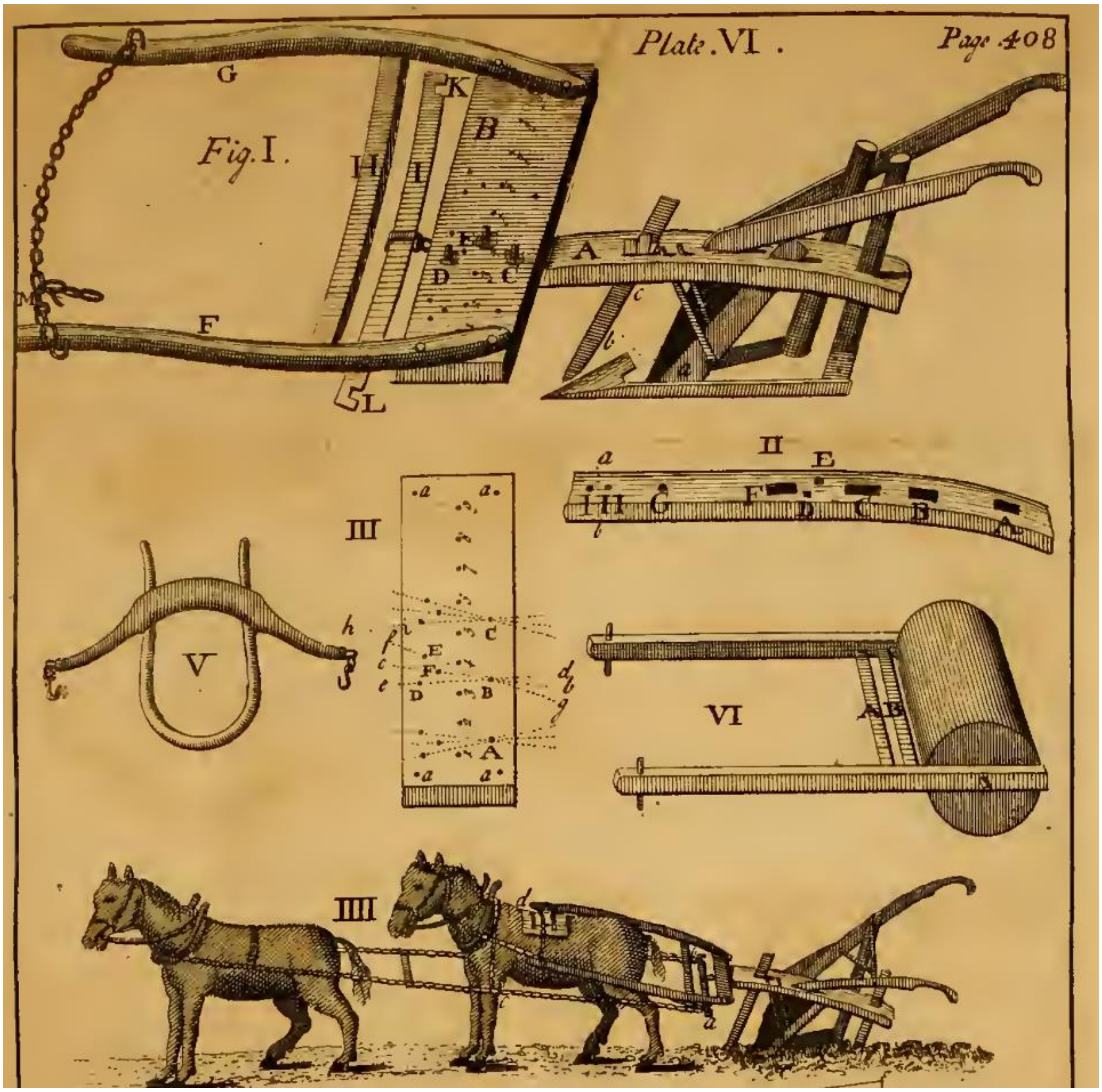

Figure 1. The Western World's first (horse drawn) interrow hoe (Tull, 1762, p. 408).

This established the basis for weed management in annual crops that continued until the advent of herbicides in the 1940-50s. Now, with the challenges facing herbicides, interrow hoes are back!

Figure 2. A 1950s Nicholson or Webb interrow hoe (left), modern modular row hoe (right) with multiple parallelogram weeder units and red and yellow finger weeder for weeding the intrarow.

However, the difference between a modern row hoe and its pre-herbicide ancestors is as large as the difference between a Model T Ford and a modern electric vehicle (EV) with self driving capabilities.

The left image in Figure 2 shows either a W.N. Nicholson & Sons Ltd. or Ernest A. Webb Ltd. interrow hoe built around the 1950s. These machines were the 'Rolls Royce' of interrow hoes in their day, and still do a high quality job, just slowly and requiring skilled labour. This compares with a modern modular row-row on the right of Figure 2. Fundamentally they still do the same thing, weeding between crop rows, but, the same as both a Model T Ford and a modern EV both drive along the road carrying people, the similarities end there.

2.6. The modern row hoe age has arrived!

Having been involved in mechanical weeding for over 30 years it feels like a revolution is now underway. Some context: Herbicide based weed science and management is something of the poor cousin of pest management as a whole, which itself is rather forgotten within wider agronomy, with it's focus on nutrients and genetics. Mechanical weed management in turn has been the poor cousin of herbicides. It has been a niche within a niche within a niche, of interest and value to a minuscule section of producers and scientists, mostly in organic farming. However, in the last ten years it has found itself propelled to the forefront of cropping weed management to become mainstream again. The wheel has nearly turned. Some of the world's largest agricultural machinery companies are now offering a suite of turn-key mechanical weeders with computer guidance systems, often by buying up existing specialist mechanical weeding companies. That the world's largest agricultural companies consider the once hyper-niche mechanical weeding marketplace to be sufficiently large they want a slice of it, speaks volumes. At the other end of the spectrum, increasing numbers of smaller, locally focused, agricultural machinery manufacturing companies are also designing and building their own mechanical weeders. That both the worlds largest and smallest agricultural machinery companies are now building mechanical weeders indicates just how far the revolution has come.

2.7. Modern, 1st and 2nd Generation row hoes

This influx of new companies, new capital, new designs & innovations, and increasing demand for row hoes has accelerated the development of modern row hoes spectacularly. Until recently row hoes have been entirely mechanical. Adjustments were made by getting off the tractor, using sockets and spanners to adjust weeding tools, clamps, springs, depth wheels etc. and then trying out the new setup. Improvements came through better designs making adjustments quicker and easier. Then in the late 1990s computer based guidance systems came along starting a revolution (section 5.23). In the last ten years row hoes have increasingly had more automation added, through hydraulic, pneumatic and electronic systems. First, downpressure control was introduced, then section control, and more recently crop gap width and other adjustments have been automated. The evolution from the original mechanical, manually adjusted row hoe designs to the more recent increasingly automated machines, suggests that row hoes designs are now sufficiently divergent that they require better descriptions. The following terms are proposed: '1st Generation' row hoes for those that are entirely mechanical and manually adjusted, and '2nd Generation' for hoes that have some form of automation and / or automatic control, e.g., have hydraulic downpressure systems. These terms are independent of the guidance system being used.

2.8. Environmental impact of mechanical weeding - energy and soil health

Concerns are often raised about mechanical weeding's energy use and impact on soil health.

In terms of energy consumed, mechanical weeding uses less energy than herbicides, when accounting for the energy expended by the tractor undertaking the spraying or the weeding and the embodied energy in the herbicide (i.e., used to create the product) which is then 'consumed' when the herbicide is applied. In a review of energy requirements of different weed management technologies, Coleman *et al.,* (2019, 2020) found that mechanical weeding used considerably less, up to ten times less (an order of magnitude), energy than herbicides. Therefore there is no evidence that mechanical weeding is more energy intensive than herbicides, rather the opposite, mechanical weeding uses much less energy than herbicides.

It should be noted that Coleman *et al.,* found in descending order that, plastic sheet mulch, microwaves, hot air, hot foam, steam, infrared, hot water, flaming and UV light were ten to one hundred times **less** energy efficient than herbicides. The energy analysis is therefore specific to the technique not chemical vs physical weed control as a whole.

Soil disturbance by mechanical weeding and its effects on soil health is more complex. Soil health here is taken to mean the overall health / quality of soil in terms of its physical health, e.g., structure, aggregation and compaction, chemical health, in terms of sufficient nutrients and pH, and biological health in terms of organic matter / soil organic carbon and biology / soil ecosystem diversity and size. First, as most mechanical weeding technologies cannot work in full residue systems, such as no-till, and only some can work in moderate residues, e.g., conservation agriculture, the use of mechanical weeding is tied to the use of some form of tillage (cultivation in British English). Generally the lower the tillage intensity, the lower the negative impacts on soil health, though it is noted that the idea that reduced tillage increases soil organic carbon has is now widely been shown to be incorrect, and, no-till soils often have higher density / lower macroporosity. Thus, when undertaking an analysis the linkage between tillage system and mechanical weeding needs to be made explicit. The relevance of the linkage also depends at what level in the agricultural system the analysis is being undertaken. For example, at the level of nation state, or geographical region, that no-and minimum tillage systems have to increase tillage to accommodate mechanical weeding clearly needs to be taken into account. In contrast at the farm system level where tillage already permits swapping mechanical weeding for herbicides then more specific question can be asked as to the relative impact of mechanical weeding vs. herbicides on soil health. The answer is there is no known research comparing the two, and it would require long term trials of more than five years to produce reliable data, and likely be site specific, e.g., depend on cropping system, soil texture etc. A theoretical analysis finds that the tillage used to prepare the seedbed involves far greater volumes of soil being impacted, and far greater amounts of energy being put into the soil to break down its structure, as shown in the energy use described by Coleman *et al.,* (2019), than with mechanical weeding. The latter is only impacting a few centimetres / inch depth of soil, from one to a handful of passes a season. Thus the relative impact of mechanical weeding compared to the tillage that preceded it is likely to be small, even minimal.

The larger concern for both herbicide and physical (including mechanical) weeding is that their primary objective - killing weeds - results in large reductions in plant species diversity and biomass. As it is living plant diversity and biomass, particularly root exudates, that drives soil health (Cotrufo *et al.*, 2022) it is now clear that the largest negative impact from both herbicides and mechanical weeding is due to their primary objective of killing weeds. The direct impacts on soil health from the chemicals in herbicides (all of them, not just the active ingredient (AI)), and the physical disturbance from mechanical weeders are likely to be insignificant compared with the impact of the reduction in plant biomass and diversity on soil health, particularly organic matter and biology / ecology (James & Merfield, 2023b). This is why there is an increasing endeavour to move to ecological weed management which aims to maximise non-crop diversity and biomass, not just for soil health but many other ecosystem and human benefits (Liebman *et al.*, 2001; Mohler *et al.*, 2021).

2.9. The debt to Organic Farming

It needs acknowledging that the existence of modern weeding machinery is almost entirely due to organic agriculture, and its prohibition of synthetic herbicides in the 1960s. Without the demand from organic farmers and growers for mechanical and physical (e.g., flame) weeding machinery, virtually no modern mechanical weeding machinery, science and expertise would exist today. Agriculture would find itself in the position of having very limited alternatives as herbicide options decline. It would be impossible to compress the last 80 or so years of practical experience, innovation, research and development in mechanical weeding, into the kind of time-spans that would be required if modern mechanical weeding did not exist, and needed to be developed in haste. In is thus chastening to consider global agriculture's position had this not been the case. It is thus very fortunate that these tools and expertise are now at its disposal, and therefore the size of the debt owed to organic agriculture.

3. Row hoes are the finale not the start of non-chemical and integrated weeding - without a whole-of-system / integrated approach failure is assured

With herbicides, weed control tends to be focused around crop establishment and the first weeks of the crop's life, for example, pre-emergent herbicides. Also, to an extent, individual crops can be compartmentalised — the weed management of one crop can be undertaken separately from others. In comparison, Integrated Weed Management and non-chemical / organic weeding, requires a whole-of-farm system approach if it is to be successful (Riemens *et al.*, 2022; Merfield, 2023b). In these systems, in-crop weeding is the icing on the cake, even the cherry on the cake. So while modern row hoes can achieve very high levels of in-crop weed management, then are not enough by themselves. If more than some 90% of weeds have not been controlled before in-crop weeding starts, e.g., through rotations, minimising weed seed rain, false seedbeds, etc. the weeds will quickly win both the battle and the war.

***Admoniti estis* — You have been warned.**

4. Where row hoes fit in the mechanical weeding pantheon

4.1. Key points

- There are now a diverse range of mechanical weeders. These are primarily divided into contiguous weeders which weed the whole field surface and incontiguous weeders that separately weed the interrow and intrarow.
- As what used to be called interrow hoes now also weed the intrarow, i.e., the crop row, the name has been changed to row hoe.
- There are two intrarow weeder approaches. High tech / discriminatory which mostly use computer vision systems and low tech / non-discriminatory that weed crop and weeds alike and rely on the crop being more resistant to the weeder than the weeds.

4.2. A mechanical weeder schema

Row hoes are one of a wide, and expanding, range of mechanical weeding equipment. In an attempt to bring some order to the many different types of mechanical weeders the following schema has been developed (Figure 3).

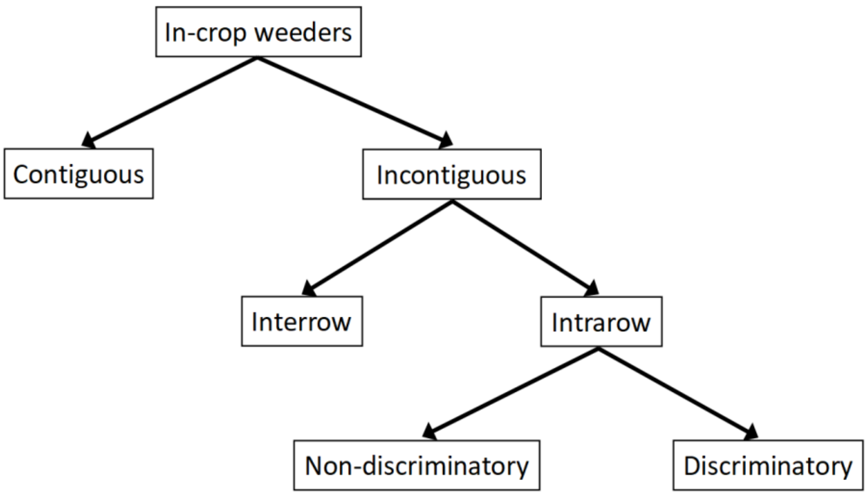

Figure 3. A schema of in-crop weeders.

In-crop weeders are first divided into two main types: contiguous and incontiguous.

4.3. Contiguous weeders

Contiguous weeders are more commonly called broad acre weeders — a common but not particularly descriptive or accurate name. Contiguous weeders weed the whole field surface, both the crop and weeds alike. Examples include spring tine weeders, spoon weeders (rotary hoes in North America) Einböck's Aerostar-Rotation and Lyckegård's Combcut. As the crop is exposed to the same weeding action as the weeds it needs to be more 'resistant' to the weeding action than the weeds. For arable / cereal farmers contiguous weeders, primarily spring tine weeders, are recommended as the entry point for mechanical weeding, before progressing to row hoes.

4.4. Incontiguous weeders

Incontiguous weeders (Figure 3) have gaps for the crop to pass through i.e., the 'crop gap' also called the crop row and intrarow, hence 'incontiguous'. None, or different weeding techniques, are applied to the crop plants in the intrarow, compared with the interrow area - i.e., the area between the crop rows. These machines were, and still often are, called interrow hoes or interrow cultivators (as in North American English where cultivation = in-crop weeding, as opposed to British English where cultivation = tillage), as they hoe the interrow but not the intrarow. However, as described below, most modern interrow hoes also have tools that weed the intrarow / crop row as well as the interrow (Figure 3), so, the name 'interrow hoe' is increasingly inaccurate.

4.5. Row hoes: what's in a name?

As interrow hoe and interrow cultivator are increasingly inaccurate names, due to them hoeing both interrow and intrarow, a better alternative is required. Row-crop cultivator, row crop hoe or just row hoe are proposed as more accurate alternatives. Row hoe is also the simplest, and so is used for the rest of this report.

4.6. Discriminatory (low tech) and non-discriminatory (high tech) intrarow weeders

Intrarow / crop row weeders are further sub-divided into discriminatory and non-discriminatory approaches (Figure 3).

Non-discriminatory intrarow weeders are akin to contiguous weeders in that the weeding action is applied to both crop and weeds and the crop plants survive as they are more resistant to the weeding action. These include finger weeders (Figure 2), torsion weeders, vertical wire weeders and mini-ridgers (section 5.18). These are 'low-tech' approaches. Discriminatory intrarow weeders use some form of sensor system to detect the location of crop plants and then weed around them. These include simple sensor wands, e.g., short length of sprung wire, as well as high-tech approaches such as computer vision systems. These detection systems then control / move a weeding device, e.g., a small hoe blade, such that it avoids the crop and only weeds the intrarow between crop plants. These are considered to be 'high-tech' approaches.

This report focuses on the low-tech / non-discriminatory intrarow weeders that are used as one of a suit of weeding tools on row hoes. The high-tech / discriminatory weeders are so diverse in approaches / design and evolving at such speed, they require a dedicated report, so are not covered here. Further, the low-tech discriminatory weeders on row hoes are now sufficiently diverse and effective that in many situations they can achieve as good, even better, intrarow weed management than the high-tech machines, often at a fraction of the cost and much higher working rates. Modern row hoes using a suite of low-tech intrarow weeders, as well as contiguous weeders, should therefore be seen as the primary means of mechanical weed management in row-crops and high-tech approaches, such as laser weeders, should be viewed as secondary and complimentary options, rather than the primary weed management tool. See section 0 for a more detailed discussion.

5. A comprehensive guide to row hoes

This is the main section of this report, which covers all aspects of the design and use of row hoes.

5.1. Key points

- There are a range of specialist terms used in row hoeing but without agreed definitions, so key terms are defined.
- A primary requirement of row hoeing is that the planter and drill rows, both the number and spacing, exactly match the crop gaps in the weeder.
- Tractor size and power is based on the need to lift the weeder on the three point linkage, not draft which is small.
- Soil, type, texture, stonyness and moisture along with weather conditions can all significantly impact mechanical weeding, just the same as for tillage, and thus require constant monitoring to ensure effectiveness.
- Mechanical weeding and herbicides are not mutually exclusive, indeed there is much to gained by their informed integration.
- Suitable weather conditions for mechanical weeding often contrast to the weather required for herbicide spraying, so when both options are available this considerably widens the weeding weather window.
- In mechanical weeding it is the weed, not the crop growth stage, that mostly determines timing of weeding, and getting the timing of weeding right is critical.
- The limit to what can be row hoed is very high density vegetables, e.g., baby salads, though new weeders for even these crops are being developed.

5.2. Defining some terms

As for much agricultural machinery there is no agreed definition of terms or names for different machines, for parts of machines etc. Even more confusingly different English speaking countries use different names for the same thing, or the same name to mean completely different things! While standard terms have been used as much as possible in this report, due to lack of agreed definitions and variation in meanings, a definition of terms used in this report is provided below. New names and terms have also been created to simplify language and be clear and consistent about what is being referred to.

Table 1. Terminology used in this report.

Name / terminology	**Description / explanation**	**Section**
A blade hoe	Horizontal knife blade hoe, with an 'A' or 'V' shape when looking downwards, with zero pitch angle, mostly used in the center of the interrow.	5.15.2.4
Blade or weeding blade	Weeding tool that uses a horizontal blade with zero pitch angle.	5.15.2
Computer guidance system	A guidance / steering system that typically uses RTK GPS or digital cameras and specialised computer software to steer / guide row- and interrow hoes.	5.23.3
Computer vision guidance system	A computer guidance / steering system that uses digital cameras to steer / guide row- and interrow hoes.	5.23
Cotyledon stage	The plant (weeds and crop) growth stage where the cotyledon leaf or leaves have emerged but before the first true leaf / leaves have emerged.	

Crop gap	The area of soil either side of the crop row left unweeded by interrow weeding tools, and /or between crop protection systems. Also called the intrarow.	4.4
Crop row	A row of crop plants, also called the intrarow.	4.4
Cultivation	North American English term for mechanically weeding crop plants. British English term for tillage.	
Cultivator	North American English term for a machine for weeding row-crops, equivalent to row hoe, interrow hoe and row-cultivator. British English for tillage equipment.	
Double steer	Another name for implement steering, where both tractor and implement (seed drill, row hoe, etc.) are independently steered by RTK GPS guidance systems.	5.23.2
Ducksfoot point	A tillage point weeding tool, with an 'A' or 'V' shape, i.e., shaped like a duck's foot, with a positive pitch angle, used for more aggressive weeding, typically used on an S spring leg.	5.15.2.4
e-spring clamp	A specialised weeding tool clamp for row-crop weeders that consists of a sprung top half the same as an S spring tine, but, then has a clamp to hold a vertical rigid tool leg. So-named as side-on they look like a small letter 'e'. Also called a range of other names including: flex tine, adjustable S tine, and vibration spring tine.	5.16
Finger weeder	A star shaped, ground driven, intrarow weeder where the fingers / star points churn soil in the intrarow killing weeds.	5.19.2
1st Generation row hoes	Row hoes that are entirely mechanical and manually adjusted, without any form of hydraulic, pneumatic or electronic automation.	2.7
Goose foot	Another name for a ducksfoot point.	5.15.2.4
Hoeing	Mechanical weeding where the weeds are killed by soil engaging tools, e.g., horizontal knife blades	
Interrow	The area of soil between the crop row / crop gap / intrarow.	
Interrow hoe	Predecessor to row hoes which only hoe the interrow and leave the intrarow unweeded.	2.6
Intrarow	The area of soil either side of the crop row left unweeded by interrow weeding tools, and /or between crop protection systems. Also called the crop gap.	4.4
L blade hoe or just L hoe	Horizontal knife blade hoe, with an 'L' shape, with zero pitch angle, designed to hoe next to the crop row.	5.15.2.2
Mechanical weeding and weeders	Any form of weeding undertaken using machinery to directly kill the weeds. Often synonymous with hoeing.	
Mini-ridger	An intrarow weeder that creates a small soil ridge of precise height in the crop row killing weeds through burial.	5.19.3
Parallelogram	The articulated system that provides depth control for the weeding tools, through a depth wheel and weeding frame.	5.13
Parallelogram headstocks	The two vertical headstocks on either end of the parallelogram bars, one connects to the toolbar the other to the weeding frame and depth wheel.	5.13.1
Physical weeding and weeders	Any form of weeding using physical techniques, for example mechanical and thermal weeding, such as flame weeding.	

Row-crops	Annual and biennial crops that are grown in clearly defined rows of any row width, established with a planter or seed-drill, e.g., wheat. This differs from the North American meaning of row-crops i.e., crops grown on wide rows such as corn and soybean.	
Row-cultivator	North American English term for a machine for weeding row-crops, equivalent to row hoe, interrow hoe and cultivator.	
Row hoe	A name defined in this report for machines for weeding row-crops using different tools for weeding the interrow and intrarow.	4.5
RTK GPS	Real-time kinematic global positioning system. GPS is more correctly called global navigation satellite systems (GNSS) as GPS is the GNSS system owned by the USA Government.	5.23.2
2nd Generation row hoes	Row hoes that have at least one form of automated adjustment and/or control, e.g., hydraulic downpressure.	2.7
Section control	Section control is used in crops on wider rows, where individual planters / drills are turned on and off using GPS to avoid creating rows crossing each other. On row hoes, section control allows weeder units to lift up at the point-rows where the drill turned off, avoiding hoeing out cross-rows.	5.13.5
Single sided toolbar clamp	A clamp for attaching a weeding unit to the main toolbar, that only attaches to one side of the toolbar.	5.12.1
Rotating spider hoe	Derived from the original Lilliston rolling cultivator, this spiral shaped rotating hoes are often used in gangs to weed the interrow.	5.15.6.1
Spring leg	Contraction of 'weeding tool spring leg', a piece of spring / flexible steel that connects the weeding tool to the weeding frame.	5.16
Sweep	North American English term for A blade hoes, and also ducksfoot and goose foot points.	5.15.2.4
T blade hoe or just T hoe	Horizontal knife blade hoe, with a 'T' shape when held upside down, with zero pitch angle, designed to hoe next to the crop row.	5.15.2.3
Telescope	A more compact alternative to a parallelogram.	5.13.8
Tillage	North American English and scientific term for manipulating soil by mechanical means in preparation for crop planting.	
Tool leg	Contraction of 'weeding tool leg', a piece of rigid steel that connects the weeding tool to the weeding frame	5.16
Toolbar	The main horizontal structure that connects the tractor's three point linkage to the weeding / parallelogram units. Also on tool carrier tractors the horizontal bars to which weeding tools are clamped.	5.12
Toolbar clamp	A clamp that attaches to the toolbar, used for mounting weeding units, depth wheels, cameras, etc.	5.12.1
Torsion weeder	Intrarow weeder consisting of thin, spring steel rods / wires that break up soil in the intrarow and pull out weeds.	5.19.5
Weeding frame clamp	Adjustable clamp that attaches the weeding tool leg or weeding tool leg spring to the weeding frame.	5.17

Weeding frame	The frame or bars on the weeding unit to which the weeding tools, via the tool legs, are attached.	5.14
Weeding tool	The soil engaging tool that does the actual weeding.	5.15
Weeding unit	The modular component consisting of the parallelogram, the parallelogram headstocks, weeding frame and weeding tools.	5.13
White thread stage	The point in plant (weed or crop) germination when the root (radicle) has emerged, but the shoot (plumule) has not broken the soil surface, i.e., before the cotyledon stage.	
Wrap around toolbar clamp	A clamp for attaching a weeding unit to the main toolbar, that encircles / wraps around the whole toolbar.	5.12.1

5.3. The key requirement of row hoes — matching the drill / planter and the hoe

The key requirement of row hoes, and all incontiguous weeders, is that the number and especially the spacing of the crop rows needs to be exactly the same for both the drill / planter and the hoe. If the drill / planter and the hoe do not line up perfectly, crop rows will be hoed out. This includes all equipment being perfectly symmetrical around the center-line of the equipment / tractor otherwise the weeder has to follow the drill direction. Typically the drill / planter and the weeder need to be the same width / cover the same number of crop rows, i.e., have the same bout width. Even with double-steer RTK GPS systems (section 5.23.2) which have astonishingly accurate bout-to-bout distance, there is still sufficient variability in the distance between bouts that trying to hoe across bouts is likely to result in killed crop, unless the crop gap / intrarow is sufficiently wide. Very large hoes that cover multiple drill / planter bouts typically have independent guidance systems for each drill bout (section 5.23). Also see section 5.22.3 on setup jigs.

5.3.1. A key limitation of row hoes — the need to standardise row spacings for multiple crops

A key limitation for row hoes, flowing on for the need to match the row spacing of the drill, planter and row hoe is the need to standardise row spacings across as many crops as possible. This is because changing the number of rows and/or row spacing (interrow distance, not the crop gap) on drills, planter and hoes is often a substantial amount of work, if it is possible at all. In particular, needing to adjust row spacing during the busy planting and weeding season is something avoided at all costs, even for row hoes that have been designed for easy adjustment. Therefore as many crops as possible need to be grown on the same row spacing. Where crops have to be grown on different row spacings, then having drills, planters and row hoes dedicated to those row spacings will likely be required, i.e., duplicate equipment will be required for the different spacings.

Standardising row spacings need not however be a major challenge. In arable crops, with their high plant populations a hectare / acre and high planting rectangularity, the area population can be kept constant for a given row spacing by adjusting the in-row seeding rate. The same can be done to an extent with vegetables, except where changing the in-row spacing / sowing rate would impact crop size, quality etc. In these situations, either area populations have to be reduced to keep inter-plant distances and rectangularity correct, or, sets of equipment for different row spacings will be required. For example, in market gardens on bed systems 30 cm / 12” row spacing can be used to grow everything from carrots with populations in the millions per ha to cauliflowers at 30,000 plants per ha. The downside is less efficient use of land for the higher population crops, where narrower rows would allow more plants per ha / acre.

5.4. Tractor size and power requirements

Row hoeing is a low draft / low power requirement operation (Coleman *et al*., 2019), as the weeding tools are very shallow and are working in pre-cultivated soil, so large / high powers tractors are not required in terms of draft (pulling power). For example, for weeders less than two meters / yards wide a 30 kW / hp tractor would be more than sufficient. For larger weeders, particularly six meters / yards wide or more, tractor size is mainly determined by the requirement to lift the full weight of the weeder on the three point linkage. The very largest weeders are towed rather than three point linkage mounted due to the weight exceeding three point linkage load capacity of most tractor sizes suitable for row-crops. In summary tractor size is based on lifting capacity rather than draft requirements.

5.5. Soil and weather conditions — contrasted with herbicides

As nearly all mechanical weeders work by tilling / cultivating the soil, and often rely on hoed weeds desiccating to achieve maximum kill, the soil and weather conditions are often critical for optimum success. Mechanical weeders are considered to kill small weeds by three methods:

- uprooting,
- severing / breaking,
- burial.

Where weeds are uprooted or severed, e.g., through the roots or foliage, i.e., not through the hypocotyl, then they have the ability to regrow unless they are desiccated to death. To minimise regrowth soil and weather conditions that maximise desiccation are best, i.e., when soil is dry and the weather is hot, dry, and windy. Good levels of weed control can still be achieved however with the right equipment even when conditions are not perfect, so it is best to weed on time in less ideal conditions than be late waiting for perfect conditions.

Where weeds are cut through the hypocotyl this is instantly lethal for small weeds, and many larger annual weeds and crop plants. Where weeds are buried, they are killed by depriving them of sunlight so they can no longer photosynthesise and capture the sun’s energy. Desiccating soil and particularly weather conditions are therefore much less important for these two methods.

However, most weeders kill weed by all three methods, with little or no control over the proportion of weeds affected by each method. Therefore most mechanical weeding achieves the highest weed kill when soil is dry, or at least not wet, and when the weather is hot, dry and windy.

This contrasts with the optimum weather conditions for herbicides, as spraying cannot be undertaken if it is too windy which causes spray drift, and in some cases when it is too low. High temperatures and dry soil can cause some herbicides to volatilise. For some residual / pre-emergence herbicides good soil moisture and/or following rain are required. Mechanical weeding and herbicides therefore have contrasting weather and soil application windows. Thus where both weeding techniques are available, the weather and soil condition windows when weeding can be undertaken are therefore much larger. For example, if it is too hot or windy for herbicide spraying those are ideal conditions for mechanical weeding. If the soil is very wet, which would impede mechanical weeding, but it is not raining and the weeds are dry, herbicides can be used. It is therefore valuable to be able to choose between mechanical and chemical weeding to suit the conditions.

For all soil-engaging weeders, soil texture (type) i.e., the proportion of sand, silt and clay, as well as moisture content and stones can all impact weeding efficacy. This is exactly the same situation as for tillage, particularly for soil moisture, for example where high soil moisture (wet soil) makes tillage impossible. The impact of soil texture and moisture on mechanical weeding is similar to tillage. For example, sandy soils are not sticky, so will not adhere to steel, they drain quickly, so high soil moisture is less of an issue, but they are the most abrasive so wear weeding tools the quickest. In comparison silts and clays are sticky when wet so can adhere to tools, they are slower draining, so suitable soil moisture levels may occur on fewer days, especially in spring when weeding is often highly time critical. Sandy soils remain friable even when very dry, while silts and clays can become very hard and difficult for weeding tools to penetrate. Even if weeding tools can penetrate harder soils, such soil often does not crumble and flow over the tools, rather it breaks into large chunks / slabs which can damage crops and reduces weed kill. Therefore, understanding the impact of soil texture and moisture on the ability of each and every weeding tool to effectively operate is critical for successful weeding.

Stones are another issue cutting across soil texture. Mechanical weeders vary in:

- Maintaining weeding efficacy with increasing amount and size of stones.
- If the weeders are damaged, or suffer increase wear with increasing amount and size of stones.

The amount and size of stones also interacts with soil texture and moisture. The effects of stonyness as well as soil texture and moisture are again similar to tillage.

Therefore, general farming experience of the impacts of soil and weather conditions on tillage is equally appliable to mechanical weeding. Thus experienced farmers constantly monitor:

- crop germination, emergence and growth,
- weed germination, emergence and growth,
- soil conditions, particularly moisture, and
- the weather forecast,

to determine when they should undertaken weeding, and be prepared to constantly adjust weeding plans as all three factors change.

5.6. Weeding time is determined by the weeds not the crop

The application timing of many herbicides is based on crop growth stages, e.g., pre-emergence and post-emergence. With mechanical weeding, timing is primarily based on the weed growth stages. Crop growth stages are a secondary consideration, mainly if the crop plants are too small and would be harmed, or if they are getting too big and have foliage broken off or will not pass through the weeder at all. As weeds grow they typically become increasingly harder to kill with mechanical weeders (and also with herbicides). This is particularly the case with contiguous weeders (section 4.3) and non-discriminatory intrarow weeders on row hoes (section 5.18). It is less of an issue for the interrow weeding tools on row hoes, as these are more aggressive. However, it is still best to aim for optimal weed sizes even when only interrow hoeing.

The optimal time for mechanical weeding is newly emerged, cotyledon stage weedlings. These weeds have used up most or all of the energy and nutrient reserves in their seeds and have the smallest amount of leaf and root area, so are at their most susceptible.

The next most optimal time is what is often called the 'white thread stage' particularly in North America. This is when the weeds have germinated but before they have emerged, i.e., where the root (radicle) has emerged from the seed but the shoot (plumule) has not reached the soil surface. The limitation of weeding at the white thread stage is that where burial (see section 5.5) is a key method of killing weeds, weeds can survive as they still have sufficient seed reserves to grow up through the additional depth of soil. There is however no known research studying this issue.

As weeds gain their first, or first pair, of true leaves, they become harder to kill. As each additional node / true leaves appears on the weeds killing them become exponentially harder. Larger weeds can also bind to, and clog up weeding tools. Thus the bigger the weeds the harder they fight, rather than the harder they fall.

5.7. Row hoes are crop and weed species agnostic compared to herbicides

Another contrast of herbicides with interrow hoeing, and to a lesser extent intrarow hoeing, are they are crop and weed species 'agnostic', in that any annual or biennial crop that is planted in rows can be row hoed. The same for weeds, to mechanical weeders they are all very similar, at least until they get larger. Hence why they are 'agnostic' to both crop and weed species.

This contrasts with herbicides, particularly selective herbicides, both pre-emergent and post-emergent. For any given herbicide there is a specific range of crops on which it can be safely used and weeds which it will kill. Some can be used on a wide range of crops, such as the grasses (monocots), and kill a wide range of weeds e.g., broadleafs (dicots). Others may be specific to one or a few crops and kill only one or a few weed species. It is only because there are lots of different herbicides that they work on all crops and all weeds. Herbicides are thus specific, sometimes very specific, about the crops and weeds they can be used on.

This is an important advantage of row hoes vs herbicides. The same row hoe can be used to weed any row-crop (as long as it is on the right row-spacing), so many different crops can be weeded with the same row hoe. No fundamental change required. Therefore the question "how would you weed a particular row-crop?" regardless of what the crop is, or what the weeds are, the answer is "use a row hoe".

5.8. Integrating row hoeing with herbicides

Mechanical weeding and herbicides are not an either-or option. The aim of Integrated Weed Management (IWM) is to integrate herbicides, mechanical and other forms of weed management. Careful thought is however required to ensure that the two approaches compliment each other rather than cancelling each other out.

For example, more expensive but effective selective / residual herbicides can be used just in the crop row, i.e., band spraying. This gives good weed control in the intrarow at early crop stages, which is the hardest to effectively mechanically weed. Mechanical weeding is then used in the interrow, where there is no herbicide. As the crop gets bigger, and the residual herbicide wears off, mechanical intrarow weeders can take over.

In contrast if a residual herbicide is used across the whole field, which needs to form an unbroken 'cap' or 'skin' over the soil surface, and that is then mechanically weeded the cap will be broken and the herbicide will no longer work. In contrast, other residuals benefit from shallow incorporation, so following their application with the right mechanical weeding can boost their efficacy.

Therefore, it is critically important to understand how individual herbicides and specific mechanical weeders interact, how best to get synergistic effects, and avoid antagonistic effects.

5.9. The limits to row hoes — very high density vegetables

While row hoes are able to achieve exceptional weed management in row-crops (as discussed in section 5.14.9) once the spacing between crops rows gets narrower than around 10 cm / 4", using a row hoe with standard weeding tools stops being practical because most of the field surface is in the harder to weed intrarow, and physically getting weeding tools between such narrow rows and still achieve effective weeding, becomes an increasing challenge. For all arable and many vegetable crops this is a not a problem as these crops are already grown at sufficiently wide row spacings. However, for the highest density vegetables, e.g., salad leaves, sown on very narrow rows e.g., 2 cm / 1”, and other crops such as carrots and onions, that are sown in double or triple lines, row hoeing is less effective or impossible due to both the small interrows and the delicate nature of the crops, especially at early growth stages. With computer guidance systems there are no issues with accurately following the rows, rather it is the small interrow space which weeding tools have to operate in which is the limitation.

To date, such production systems can only be effectively weeded with herbicides - i.e., herbicides have allowed such systems to be created. Organic growers of such crops have had to increase the row-spacing, and revert to single rows so they can row hoe them. However, there are novel interrow weeders coming to market, e.g., feldklasse.de which use a rotary weeding tools that are able to weed the interrows of very narrow crop rows. There are also the robotic weeders that kill weeds individually, e.g., laser weeders, which can weed both interrow and intrarow — at a cost. Electrical interrow hoes may also have potential to weed between very narrow rows (section 5.15.2.5). Therefore while row hoes are highly effective, very narrow row spacings are still a significant challenge, but one that is being progressively solved.

5.10. Modular, parallelogram, weeding units — a ‘Swiss army knife’ weeding platform

5.10.1. Key points

- There is a considerable amount of technical details in the design of row hoes.
- Modularisation allows row hoes designs to be highly flexible and their size is only limited by machinery strength and practical in-field considerations.
- The toolbar connects the tractor to the modular parallelogram weeding units.
- The parallelogram allows the weeding frame to maintain the correct height above the soil and parallel with the ground along its full length.
- The design of weeding units is really important to the overall effectiveness of a row hoe.
- Achieving the correct downforce on the weeding frame has lead to pneumatic and hydraulic systems that now permit advanced features such as section control
- Modern, modular row hoes are less of a weeder themselves, they are more of a platform for a diverse range of weeding tools that are mixed and matched to the crop, weed, soil and weather conditions — hence why they are the ‘Swiss army knife of mechanical weeders’.

Figure 2 shows a multitude of differences between pre herbicide era interrow hoes and modern row hoes. A key difference is on older machines the weeding tools were often built into the weeder, compared with new machines where a wide range of different weeding tools can be swapped in and out to match crop, weeds and soil conditions. Also, older interrow hoes were often a single structure. It was possible to add and remove weeding tools, e.g., to accommodate different numbers of rows, but, that often required the whole weeder to be dismantled. In the intervening years the design of row hoes has converged to a single approach — that of the modular, parallelogram, weeding unit (Figure 2). ‘Parallelogram’ refers both to the geometric shape of the height / depth control system that keeps the weeding frames at the correct height and that it also keeps them parallel to the ground (Figure 4).

Figure 4. Modular parallelogram weeding unit on a row hoe. Dotted white line highlights the geometric parallelogram shape of the depth control system.

Modularisation means that any width, numbers of crop rows and widths can be covered by a single design, simplifying manufacturing, weeder assembly and setup.

That practically all manufactures have converged over the decades on the same modular parallelogram design indicates that it is an optimal solution for row hoes. For simplicity, these modular parallelogram units are called 'weeding units' from now on. See section 5.13 for information on weeding frames and section 5.14.9 for mounting of weeding tools.

This modularisation and separation of the weeding tools from the rest of the weeder has turned row hoes into a 'weeding platform', rather than a weeder in and of themselves. A wide range of different weeding and even non-weeding tools can be mounted on the weeding frames allowing a diverse range of crops and weeds to be tackled by the one machine. Hence why they are 'The Swiss army knife of mechanical weeders'. Modularisation also allows for row hoes to be setup to weed crops on ridges or any bed / ground shape making them highly flexible (Figure 5).

Figure 5. Modular row hoe for ridge crop weeding.

5.10.2. Non-parallelogram row hoes

This report mainly covers parallelogram based row hoes, as these are now the dominant design. However there are a small number of other designs of row hoes, such as rotary-tillers, brush weeders, basket weeders and simple non-parallelogram interrow hoes, often with niche applications, as well as both old and new tool carrier tractors which are briefly covered in section 6.

5.11. Tractor mounting approaches

Prior to the advent of computer guidance systems in the late 1990s, there were multiple ways of tractor mounting interrow hoes, often with a range of challenges, see section 5.23.6. With computer guidance systems, rear three point linkage mounting has become standard, making mounting of row hoes as straightforward as other rear mounted tractor equipment. However, for smaller hoes, the use of manual steering, and non-rear three point linkage mounting is still used. See section 5.23 for more information on guidance systems including manual steering, and section 5.23.6 on alternative mounting approaches.

5.12. Three point linkage toolbar

The 'toolbar' is what connects the tractor's three point linkage to the individual weeder units (Figure 6). The term 'toolbar' is used to differentiate it from the 'weeding frame' on which the weeding tools are mounted and which in turn is connected / mounted to the parallelogram system.

Figure 6. Individual modular parallelogram units (green) attached to toolbar (yellow).

Typically the toolbar is a large box section, e.g., 100 mm / 4" square. Toolbars, especially those wider than the tractor, have depth wheels to ensure the toolbar is at the right height above the ground, reduce vertical flex of the toolbar and take weight off the three point linkage.

There are two different means of attaching weeding units, depth wheels, headstock etc., to the toolbar: one sided and wrap around clamp systems

5.12.1. One sided vs. wrap around, toolbar clamps

Wrap around toolbar clamps attach a weeding unit to the main toolbar, by completely encircling / wrapping around the whole toolbar (Figure 6). In comparison, one sided clamps attach to only one side of the toolbar (Figure 7). There are pros and cons to both approaches.

Figure 7. A range of different wrap around attachment systems for weeding units, depth wheels etc.

Figure 8. A range of different one sided toolbar clamping systems for weeding units, depth wheels etc.

The advantage of wrap around clamps is they are simple from an engineering perspective. Off-the-shelf steel can be used for the toolbar and in the clamp, with standard fasteners (e.g., nuts and U bolts) being used, thus keeping costs down and allowing for easy repairs. The downside of wrap around clamps is where there are items mounted on both the front of the toolbar, such as the three point linkage headstock (the position of which typically can't be moved), depth wheels, camera mounts, etc., is that those are locations where weeding units cannot also be mounted as the clamps get in each others way.

The main advantage of one sided mounting systems is that any item can be placed on either side of the toolbar without any risk of interfering with items on the other side, as shown in the left image in Figure 8. The main downside is that it requires custom toolbars and clamps, increasing costs, and potentially making repairs more challenging.

Which system is best depends on a number of factors. Typically items connected to a toolbar (such as the headstock, depth wheels and weeding units) are rarely, if ever, moved once they are setup for a given cropping system. If all the items can be setup without interfering, and many toolbars are designed to accommodate typical row spacings for common crops, or they are built for specific row spacings, then wrap around clamp systems work just fine. Where less common row spacings are used, there are large numbers of weeding units, where weeder units need to be adjusted sideways on a frequent basis and/or there is a need / desire to have weeding units in an exact location, then, one sided toolbars are the better option.

On larger hoes with folding sections, the hinge point(s) in the toolbar typically cannot have a weeding unit clamped right on the join. It is thus important to make sure that the joins are in different locations to where the weeding units need to be clamped. Some manufactures have systems that allow weeding units to be positioned over the hinge point. Or hoes are manufactured so the hinges don't conflict with mounting positions.

5.12.1.1. Ease and accuracy of mounting clamps / weeding units on the toolbar

Partly related to wrap around vs. one-sided toolbar clamps is ease and accuracy of clamp mounting. As can be seen in Figures 6 to 8 some weeding units, depth wheels etc., have to be physically supported as the clamps are put in place, e.g., bolts threaded through holes in plates, and then nuts tightened. This makes the job of mounting the items onto the toolbar more difficult, often considerably. Then ensuring that the item is accurately positioned on the toolbar can also be challenging as tightening the clamp can cause the item to move on the toolbar.

The alternative is 'drop-in-place' mounting system where the item can be placed on the toolbar and its weight keeps it in place. Also there is zero movement when the clamp is tightened (Figure 9).

Figure 9. One sided toolbar with drop-in-place mounting system.

Most drop-in-place clamp systems only work on one-sided toolbars. The same as for one sided vs. wrap around toolbar attachment systems, whether drop-in-place clamps are worthwhile or not is going to depend on how often the items on the toolbar need to be repositioned, the level of accuracy required in the mounting positions and how quickly the (re)positioning needs to be done.

5.13. Parallelogram design

The parallelogram (Figure 4) is the heart of modern row hoes:

- It accurately controls height of the weeding frame above the soil, thus allowing the depth of the weeding tools to be precisely controlled.
- It keeps the weeding frame horizontal / parallel to the soil, ensuring all weeding tools are at the correct depth.
- It allows individual weeding units to be able to follow considerable variations in the height of the ground across the width of the hoe, thus allowing for wide hoes with a single toolbar to accommodate both flat and undulating ground.

Despite being conceptually simple, there is a considerable complexity to a well designed parallelogram.

5.13.1. Parallelogram basics

The parallelogram works by having one parallelogram headstock clamped to the toolbar, with the other headstock being attached to both a depth wheel and the weeding frame (Figure 10). As the depth wheel follows the ground the parallelogram allows the height between the ground and the toolbar to vary while keeping the weeding frame parallel and at the same height from the ground.

Figure 10. Different parallelogram designs - variations on a theme.

5.13.2. Parallelogram arm length and accommodation of ground height variation.

Parallelogram arm length differs considerably among row hoes, which determines the amount of height variation the parallelogram can accommodate. Those designed for vegetable crops grown on flat ground with a high degree of soil tillage, producing a flat even field surface, typically have short arms, so they can only accommodate smaller differences in soil height, e.g., 30 cm / 12". Hoe width on vegetable hoes is typically one to three beds so the total width is not great, so there is not much side-to-side height variation to accommodate either. Those designed for arable crops on fields with larger variation in soil height, and/or larger width hoes need parallelograms with longer arms which can accommodate larger variations in soil height across the hoe width, e.g., one meter / yard.

5.13.3. Depth wheels - adjustment and construction

To adjust the height of the weeding frame from the soil surface, on most weeding unit designs the depth wheel is moved up and down. This is typically on some form of threaded winder or a pin-and-hole system. A few designs keep the depth wheel fixed and move the weeding frame up and down on the parallelogram headstock.

Most depth wheels use semi-pneumatic tyres, which can't be punctured and that shed sticky soil. However, all forms of wheels and tyres are used, from full steel with and without center ribs, to solid rubber, to full pneumatic, with the usual pros and cons for each.

5.13.4. The utter importance of parallelogram horizontal rigidity

While the parallelogram needs to be able to move completely freely in the vertical plane (up and down) it needs to be as rigid as possible in the horizontal plane (left to right). With computer guidance systems being able to operate at centimetre / half inch or even greater accuracy, if the parallelogram allows the weeding frame to move side-to-side by more than by a centimetre / ½" then it could be less accurate than the guidance system, potentially resulting in the crop being damaged. A key test of a parallelogram is how much side-to-side movement there is at the back of the weeding frame. When the whole row hoe is off the ground (e.g., lifted on three point linkage) hold the back of a weeding frame, and with as much force as possible, move it side-to-side. In a perfectly rigid parallelogram pushing on the weeding frame results in the whole row hoe moving on the tractor linkage (or even swaying the tractor) there should be no movement within the parallelogram, or the rest of the weeding unit. If there is movement within the parallelogram or weeding frame, on a new hoe this indicates poor design, on a used hoe that maintenance is required.

The design of the pivots and bars of the parallelogram are key to its horizontal rigidity. This requires pivot hinges with large diameter pins (bolts) which have large wear / contact surfaces, or better ball bearings, and which are greasable, all of which can be tightened without causing the hinge to tighten and impede free vertical movement. The arms / bars connecting the hinges must have zero horizontal flex, i.e., be horizontally completely stiff, for example flat bar or hollow section placed with the wider dimension horizontal (Figure 11).

Figure 11. Parallelograms with high horizontal rigidity due to large diameter hinges or bearings that can be greased and parallelogram arms / bars that have zero sideways flex.

Sub-optimal designs have hinges with small contact areas, limited ability to be lubricated so are prone to wear, and/or the connection arms are positioned vertically so they can flex horizontally (Figure 12).

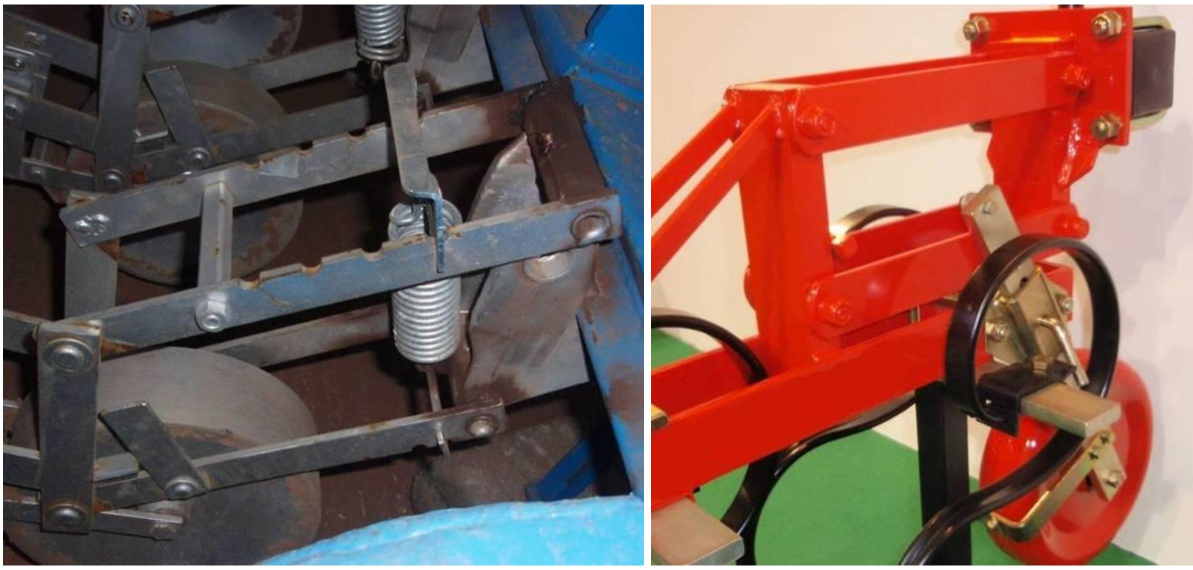

Figure 12. Sub-optimal parallelogram designs with small hinge contact areas, with limited lubrication options, which are prone to wear, and connecting arms / bars orientated vertically which can flex sideways, therefore allowing horizontal movement of the weeding frame.

It is noted that it is somewhat counter-intuitive to have the arms of the parallelograms horizontal and not vertical.

5.13.5. Parallelogram / weeding frame downforce

For a basic weeding unit it is only the weight of the floating part that exerts downforce. This may be insufficient to force the weeding tools into the soil and minimise bounce of the weeding unit, such that additional downforce is required. There are two main approaches to applying downforce: springs and pressurised systems such as hydraulics or pneumatics. The third is the old 'trick' of adding extra weight to the weeding frame, e.g., by hanging some tractor front end weights on the frame. Simple, effective but not an elegant or lightweight solution, so these are not used in commercial row hoes!

Springs are clearly simpler, and thus cheaper, than pressurised systems, but, the issue for springs is there is no **simple** way of attaching the springs to a parallelogram whereby the downforce created by the spring is constant as the parallelogram moves through its arc. This is because as the parallelogram moves up and down the distance between the two headstocks varies from close to zero when the parallelogram is fully up or down, to the maximum distance apart when the parallelogram creates a rectangle at its mid position, distance 'A' in Figure 13. A spring between the headstocks will therefore change length as the parallelogram moves and therefore change the force it applies.

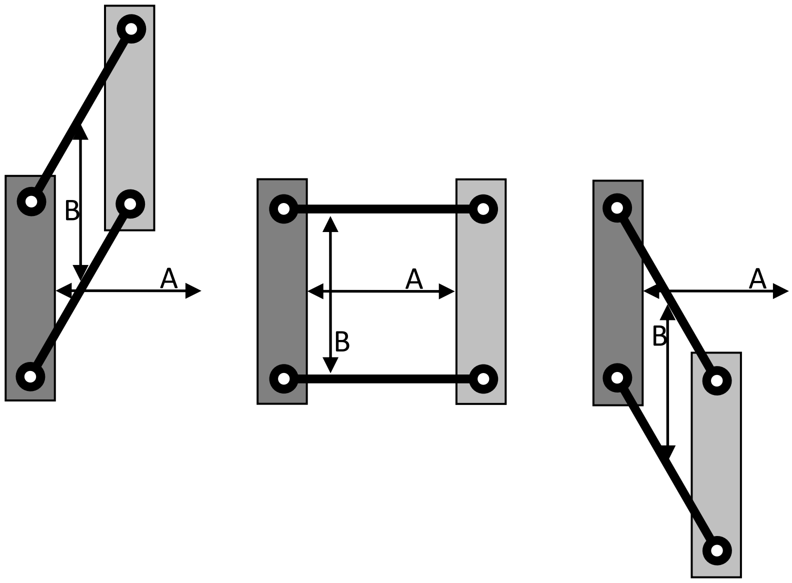

Figure 13. The distance 'A' between the two headstocks of a parallelogram changes as the parallelogram moves through its arc, while distance 'B' between the two parallelogram arms / bars stays constant.

The opposite is true for the distance between the parallelogram arms, which remains constant regardless of the parallelogram position. So a spring attached at right angles (orthogonally) to the two arms has the constant length 'B' in Figure 13. Therefore it cannot exert any downforce on the parallelogram; rather it is trying to pull the two parallelogram arms together against their hinge points.

Thus a very diverse range of spring anchoring locations and systems have been developed, including complex systems such as having additional pivot points (Figures 2, 10, 11 and 12). But, regardless of a spring system's design it is hard to avoid it creating uneven downforce as the parallelogram moves up and down, resulting in the depth of weeding tools potentially varying, resulting in poorer weed control.

To keep a consistent downforce on the weeding frame as the parallelogram swings through its full arc requires a hydraulic or pneumatic system as these can achieve constant pressure throughout their full range of movement (Figure 14). Clearly this comes at considerably greater complexity and cost than spring systems.

More recently hydraulic / pneumatic downforce systems have been used for section control. The downforce system on individual weeder units / parallelograms is used to automatically lift the weeder unit up and down on point rows so it avoids hoeing cross rows. This then also requires each parallelogram to have its own individual control mechanism (valve, etc.). Without section control a unified, and thus simpler, pressure system can be used.

Figure 14. Hydraulic and pneumatic downforce systems on parallelograms.

Whether spring based downpressure is sufficient or pneumatic / hydraulic systems are required depends on a range of factors, but mainly how level or undulating the fields are and how much down force is required. On level ground where the parallelogram may only be moving up and down by ± 10 cm / 4” the variation in spring down pressure may not be an issue. More undulating fields and harder soils requiring more downforce may be better served by pneumatic / hydraulic systems. Only pneumatic/ hydraulic systems can provide section control. That more recent designs of row hoes are using active pressure downforce systems indicates that the benefits are outweighing the cost, though section control may also be driving the use of active pressure systems.

5.13.6. Horizontal parallelograms

An interesting alternative to the standard vertical headstock parallelogram with horizontal arms is where the headstocks are horizontal and the arms are vertical i.e., hanging, so that the draft of the weeding tools creates downforce. Kyuho Co., Ltd. in Japan (q hoe.com) and SAS Binnove in France (binnove.fr) both use this approach.

5.13.7. Locking up parallelograms

When the toolbar is lifted on the three point linkage all the weeder units will drop to their lowest point on the parallelogram’s arc of movement, resulting in them being close to the ground, which may create issues e.g., for road transport. Most parallelograms have systems for locking the parallelograms at the center or better top of their arc to maximise ground clearance for transport etc. Active pressure systems may also have locks, as while the weeder units can be raised by the pressure system, reasons such as road transport, may require that the units are physically locked in place. Again, designs vary considerably: from systems where the parallelograms can be locked simply by dropping the toolbar low to the ground or raising the active system to full height and then the locks engage automatically, to those that require each individual weeder unit to be manually lifted and locked in place with a pin or similar, i.e., usability varies considerably.

5.13.8. Compact weeding units and telescopes

Most weeding units are somewhat linear in their design - the clamp is attached to the back of the toolbar, next there is the parallelogram, then the depth wheel and its headstock, finally followed by the weeding frame. This can make the weeding units quite long, e.g., more than 1.5 meters / yards. This can create issues such as turning on headlands and where the hoe is guided by steering the tractor lateral movement at the end of the weeding units due to the back of the hoe swinging (the tail wagging) in the opposite direction to the tractor steering wheels, may be sufficient to cause crop damage. A few row hoes are designed to be more compact, through approaches such as clamping to the front of the toolbar, having the parallelogram wrap around the toolbar and positioning components such as the depth wheel under the toolbar, as shown in Figure 15.

Figure 15. Compact weeding units, right photo Bigham Ag bighamag.com.

For situations where the row hoe needs to be very compact, the primary alternative to parallelograms are ‘telescopes’ where a central shaft that is attached to the weeding frame and depth wheel runs inside a hollow steel section, typically on bearings (Figure 16). These use both passive downpressure, i.e., use the weight of the central section and the weeding tools, or they can use sprung or pressurised downpressure systems, e.g., hydraulic. There are only a few manufactures making telescopes.

Figure 16. Telescope depth control systems.

5.13.9. Interrow or intrarow centered weeding units?

Most weeding units are designed to be centered on the interrow, i.e., the depth wheel runs down the center of the interrow. Some high precision weeders designed for vegetables, particularly direct sown crops, have pairs of depth wheels that run either side of the crop row to give the most accurate depth control possible. This thus places the centreline of the weeding unit down the center of the intrarow / crop row. This creates more flexibility, and potentially accuracy, in placing weeding tools designed to work right next to the crop row (Figure 17). However, this limits the height of the crop that can be hoed before it starts hitting the bars on the weeding frame and other parts of the weeding unit, so this approach is generally not used for tall crops such as maize, or crops that need to be weeded when they have grown wider.

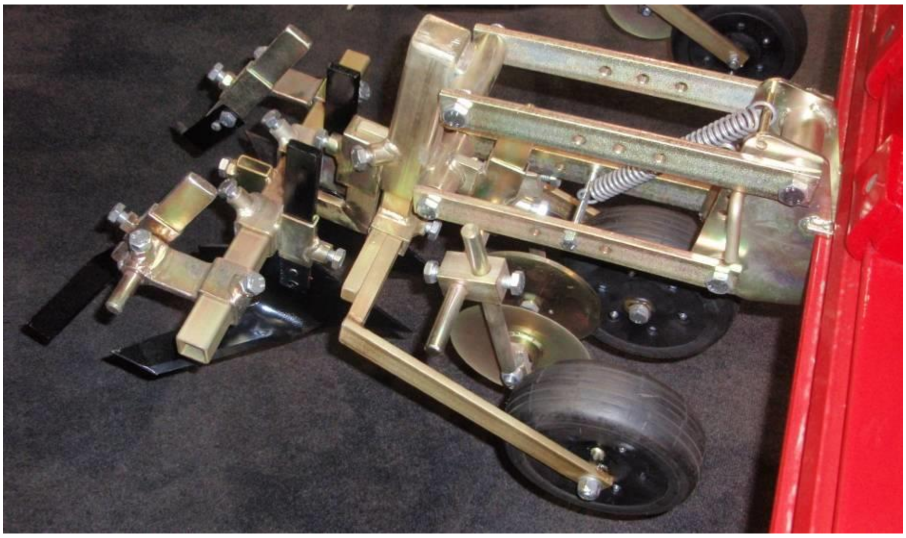

Figure 17. Intrarow centered weeding unit with twin depth wheels running either side of the intrarow / crop row.

5.14. Weeding frames

5.14.1. Key points

- A well designed weeding frame that allows a range of types and number of weeding tools to be attached and easily adjusted is an important component of a good row hoe.
- Weeding frame design needs to be matched to crop type and row spacing to ensure all the required weeding tools can fit onto the frame.
- There are two main weeding frame design approaches: end connected and center connected. Center connected is clearly now the preferred and more flexible approach.
- The width of weeding frames / the number of weeding units is driven by crop row width and configuration, i.e., continual rows in arable and with wheelings and beds in vegetables.
- To maximise the efficacy of row hoes, the maximum amount of the field surface needs to be interrow and the minimum in the intrarow., i.e., the width of the interrow needs to be maximised and intrarow minimised.

The weeding frame is where the different weeding tools are attached to the row hoe. The weeding frame typically mounts onto the rear parallelogram headstock and is thus connected to the depth wheel(s). This ensures that the weeding frame is parallel to the ground along its entire length and at the correct height for optimal weeding tool efficacy.

5.14.2. Weeding frame bars - size and shape

The weeding frame consists of a series of horizontal bars of varying shapes, including flat bar, round, hollow section (box) and solid square bar, both on the square and the diamond (Figures 18 and 19). There are pros and cons for all bar shapes and sizes, and there does not appear to be a trend towards a particular shape or size. One consideration is if the size / shape is unique / proprietary to the manufacturer so that only their clamps will fit on the weeding frame bars, or, if it is a common size, e.g., 50 mm / 2” box used in tillage equipment frames, thereby allowing cheap, widely available, generic clamps to be used.

5.14.3. What makes for the perfect weeding frame?

What makes for a perfect weeding frame in one situation may be a poor design in another, i.e., there is no one perfect weeding frame. There are thus a range of design issues to be considered to choose the right weeding frame for a given situation.

5.14.4. Having sufficient space for weeding tools - how many bars and how wide?

The biggest issue in weeding frame design is having sufficient space both side-to-side and front-to-back to be able to mount all the required weeding tools without them interfering / clashing / getting in each others way. Clearly if two tools need to be mounted in the same place, or the soil engaging parts are touching, then they are going to interfere. However, many tools need more space around them than not just quite touching the next tool, e.g., to allow soil and weeds to flow off them. This is just the same as for many tillage tools where tines are spaced some distance apart to allow soil and residue to flow around them. It is therefore vital when choosing a row hoe and setting up the weeding frame that there are sufficient mounting locations, both horizontally across the weeding frame bars and the total number of bars front to back to accommodate all the required weeding tools without them interfering with each other.

Larger weeds have considerable potential to block weeding tools with insufficient clearance between them. So, while small weeds may flow between weeding tools, bigger weeds may cause blockages. One of the most frustrating things in row hoeing to have hoes continually block with bigger weeds, which requires time-consuming manual clearing, plus the crop damage done by the blockages. Thus, it is far better to have more clearance than less.

It is therefore not possible to give a simple answer to how many and how wide the bars should be as the configuration of the crop and the number of rows weeded by each weeding unit varies widely. For example, cereals on 15 cm / 6” row spacings may have one weeding unit per interrow with just one weeding tool mounted on the weeding frame. Or for the same crop, one weeding unit could be set up to cover four rows with three weeding tools, one per interrow, so they can all be on the same weeding frame bar. In vegetables, there may be L or T hoes weeding next to the crop, plus a crop guard or side cutting disks, an A blade hoe in the middle of the intrarow, mini-ridgers and finger weeders mounted at the same time but one set lifted up, and a mini-tine weeder at the rear. Clearly these are going to require a weeding frame with multiple bars to be able to successfully attach all of them.

Older row hoes typically had just two to three horizontal bars. Newer hoes, particularly for vegetable systems, typically have more bars, including having offset left and right bars, to facilitate the increasing number of weeding tools being mounted on a single weeding frame. There may also be separate mounting systems on the main toolbar for finger weeders which don’t need to be kept perfectly parallel to the soil surface (see section 5.19.2) so freeing up space on the weeding frame.

Thus, understanding what the best weeding tools are, and how and where to mount them can be complex, and getting good advice and working through the details is time and money well spent.

5.14.5. The two main weeding frame designs: end and center connected

There are two main approaches to weeding frame design, though the variation of approaches is so diverse the categorisation is not totally hard and fast:

1. **End connected bars**: The horizontal bars are joined and supported at their ends, so that weeding tools can be placed on and around the center line of the weeding frame without obstruction. Typically the horizontal bars are permanently fixed in place (Figure 18).
2. **Center connected bars**: The horizontal bars are attached at their centers to a frame that extends from the rear parallelogram headstock often with the bars being adjustable / removable (Figure 19).

Figure 18. A range of end connected weeding frames.

Figure 19. A diverse range of center connected weeding frames.

As can been seen from Figures 18 and 19 center attachment is far more common than end attachment. Center attachment is also the preferred design on newer row hoes. Both of which indicate this center attachment is proving the best and wining out. There are still pros and cons for both approaches.

5.14.6. End attachment pros and cons

End attachment gives complete freedom to mount multiple weeding tools on and close to the center line of the weeder unit. Most center attached frames have one position for one weeding tool mounted exactly on the center line, so, it is not possible to mount more than one tool directly on the center line.

End attachment also naturally creates a crop gap and continual surface for taller crops to slide between the weeding frames. The right most image in Figure 18 shows a specialised maize / corn row hoe designed so the crop plants pass between the weeding frames, with bent gathering bars at the front end of the frames, and a very high clearance toolbar (not shown), which allows plants well over a meter / yard high to be hoed at speed.

Where crops are not passing through a gap between adjacent weeding frames then the distance between the edges of the weeding frames becomes a consideration. Do the weeding frames need to be close enough to each other so that weeding tools on adjacent frames overlap with each other? This requires good lateral parallelogram stability (section 5.13.4) so the weeding frames stay parallel. As can be seen in the center image in Figure 18 the center and left weeding frame are accurately aligned, but the center and right weeding frames are not.

Where crops pass under the weeding frames, the height of the frame off the ground puts an upper limit on crop height, because if the crop is too tall it will be damaged as it bends under the frames.

With end attachment weeding frames it is not possible to slide the weeding tool clamp onto the end of the bar. Most clamps can be fitted (reasonably) easily onto a bar where they need to be placed, but, not always.

End attachment weeding frames by their nature have the bars on the left and right of the weeding unit in a straight line.

5.14.7. Center attachment pros and cons

The pros and cons of center attachment are to an extent the flip side of end attachment.

There are a number of advantages of having the bars clamped to the weeding frame, rather than permanently attached (e.g., welded). At the design stage and when assembling the weeding frame the width of the weeding frame can be easily altered by sliding the bars sideways across the frame, and using different length bars. Also the number of bars can be varied. This allows a single weeding frame, to cover a wide range of widths and depths, compared with end attachment where the frame width and number of bars is fixed during manufacturing.

A key issue is that weeding tools cannot be mounted at the attachment point of the weeding unit to the toolbars. While there is typically one central mount position, not being able to mount weeding tools close (but not exactly on) the center line may be an issue. Solutions include weeding tools with dog-leg (bent) shafts, or tools with longer blades.

With center attachment crops can pass either under or between weeding frames. Where taller crops pass between frames, there has to be a sufficiently large gap between the ends of bars on adjacent frames that the crop can pass through without hitting the ends of the bars and being damaged, particularly at high forward speeds. Crop protection systems (section 5.21) may help minimise crop damage, and/or guide bars can be attached to the end of the frame bars for the crop to slide along. And, the same as for end attachment, the height of the frame off the ground puts an upper limit on crop height when passing under the frame.

On some weeding frame designs the bars on the left and right of the frame’s center line can be offset front to back. This can help increase the distance between weeding tools on the same frame, and, also means that the bars on adjacent frames don't hit each other, and can be even set to overlap if required.

5.14.8. Weeder frame / weeder unit width

There are multiple factors that determine optimum weeding frame width and thus the distance between and number of weeding units (Figure 20). The key factor is crop type and spacing, for example if the crop is continuous (arable) or in beds (vegetables). An important point is that one weeder unit can weed several crop rows. Also not all weeding frames on a hoe need to be the same width, e.g., weeding frames behind the tractor wheels may match the tyre width and be a different width to those hoeing the crop.

Figure 20. Wide, medium and narrow weeding frames and weeder unit spacings. Right photo Garford Farm Machinery Ltd. garford.com

The more weeder units the more a roe hoe weighs and costs, so, economics pushes the number of units downwards. However, there is clearly a limit to how wide a weeding frame can be and work effectively, because as width increases the potential for differences in soil height between the depth wheel location and the weeding tools positioned further from the depth wheel means their depth control becomes sub-optimal and they will no longer weed effectively. Weeding frame width and number is thus to an extent a balance of economics and practicalities.

Where the ground contour is flat, weeding frames can be wider, and conversely, the more uneven and undulating the ground, the narrower weeding frames need to be. Flat of course, is a relative measure. Flat means that the soil between the depth wheel and a weeding tool is sufficiently level that the weeding tool is at the correct operating depth. This is both the distance side-to-side and front-to-back: a very long weeding frame on uneven ground may result in the weeding tools at the very back of the weeding frame being at the wrong depth, even if they are inline with the depth wheel. Overall this means that weeding frames of around three quarters of a meter / one yard is the maximum practical width.

A newer issue for the number of rows weeded by one weeder unit is section control. Typically section control is only used on wider spaced crops e.g., > 40 cm / 16”. If multiple rows are weeded by one weeding unit this may result in section control lifting the weeder up or dropping it down to early or two late for some point rows. Logically for section control there needs to be one weeder unit for every interrow, i.e., one weeder unit between two crop rows.

If there is a need to hoe tall crops, e.g., maize, that won't fit / bend under the weeding frame, so that the crop needs to pass between weeding frames, then one weeder unit per interrow is also required, regardless of other considerations.

For arable crops, such as wheat, with large numbers of plants in the row, and where there is no gap for the tractor wheels, i.e., the crop rows are continuous across the field, row spacing is the primary driver of weeding frame width. For rows < 20 cm / 6” one weeding unit / weeding frame typically covers several rows. Normally they cover an even number of rows, as the depth wheel runs between the rows / in the interrow, so the weeding frame extends to the two rows, one on either side of the wheel, then four rows, two on either side of the depth wheel, etc. For example in 10 cm/ 4” rows, one weeding unit covering four rows requires a ~30 cm / ~12” weeding frame, so it is slightly narrower than the distance between the two outside rows, so it does not conflict with the next door weeding frames.

There are also very narrow parallelogram systems designed to go between each row of < 15 cm / 6” rows. Where row spacings are > 30 cm / 12” having one weeder unit per interrow, i.e., one unit between two crop rows is the most common approach.

Where tractor wheelings are significantly lower, harder or otherwise vary from the rest of the field, such as vegetable systems (see below) weeding units dedicated to the wheelings may be used.

For vegetable bed systems the bed width as well as the crop row spacing is important. Where wheelings and bed are at different heights, even just a few cm / inch, can have an impact on weeding effectiveness, especially where soil density in the wheeling is much higher than the bed. Therefore weeding units dedicated to the wheelings, and potentially the sides of the bed if they are raised, with more aggressive weeding tools, are required. Then, the width of the bed top and the number of rows drives the number of weeding units. For very level beds, two weeding units may work, but more typically four are used, or one unit per interrow. There is also the option of twin depth wheel systems, where the weeding unit is centered over the crop row (section 5.13.9) which by design requires one weeding unit per crop row.

5.14.9. Row spacings and intrarow / crop gap size — size matters

Over the centuries since Jethro Tull first invented the seed drill, a vast amount of time has been spent researching, discussing and debating crop row spacing from multiple perspectives including practicalities, rectangularity, populations, yield and much more. The requirements of row hoeing are yet more variables to add to the mix. There are two key points:

- The wider the crop row spacing the more of the field surface is interrow,
- The narrower the intrarow / crop gap the more of the field surface interrow.

The two clearly interact: wide crop rows with small intrarows have the maximum proportion of interrow, while narrow crop rows with large intrarows has the smallest proportion of interrow. While intrarow weeding tools are now highly effective at weeding the crop row they can never be as aggressive as interrow weeders or they will kill the crop. Thus the more of the field surface in the interrow the more of the field that is weeded by aggressive interrow weeders and therefore more likely to achieve better overall weed control.

Figure 21 visually shows the proportion of the field surface in the interrow and intrarow when moving from 30 cm / 12” crop rows to 10 cm / 4” crop rows on the same intrarow width. With closer rows much less field surface is under the interrow and more is under the intrarow.

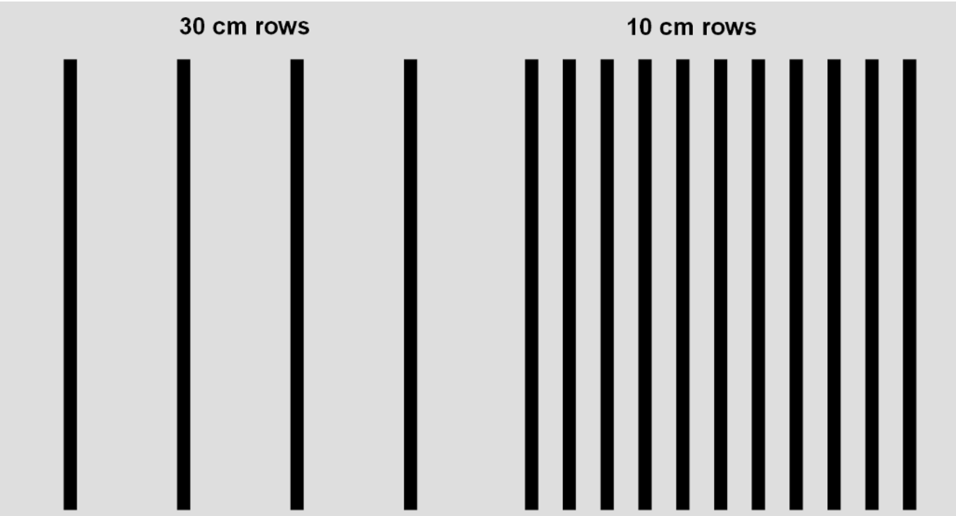

Figure 21. The same 4 cm / 1 ½” wide intrarow / crop gap at 30 cm / 12” (left) and 10 cm / 4” (right) row spacing, visually showing that as row spacing narrows an increasing proportion of the field surface is in the harder to weed intrarow.

With manual steering of interrow hoes, including tool carriers, it was common to have a 10 cm / 4” crop-gap / intrarow. With computer guidance systems, more precise and accurate drilling and hoeing machinery, crop gaps of 4 cm / 1 ½” are possible, thought at practical limit. A 4 cm / 1 ½” crop gap means that the crop plant in the middle of the intrarow has less than 2 cm / ¾” between the plant and the hoe blades, which could be travelling at more than 15 kph / 10 mph!

Figure 22 shows the percentage of the field surface under the interrow for a range of row and intrarow widths. Where the percentage of the field surface falls below ~40% the value of row hoes, and their ability to aggressively weed the interrow, is lost, and using a contiguous weeder, like a spring tine weeder or spoon hoe, becomes a better option.

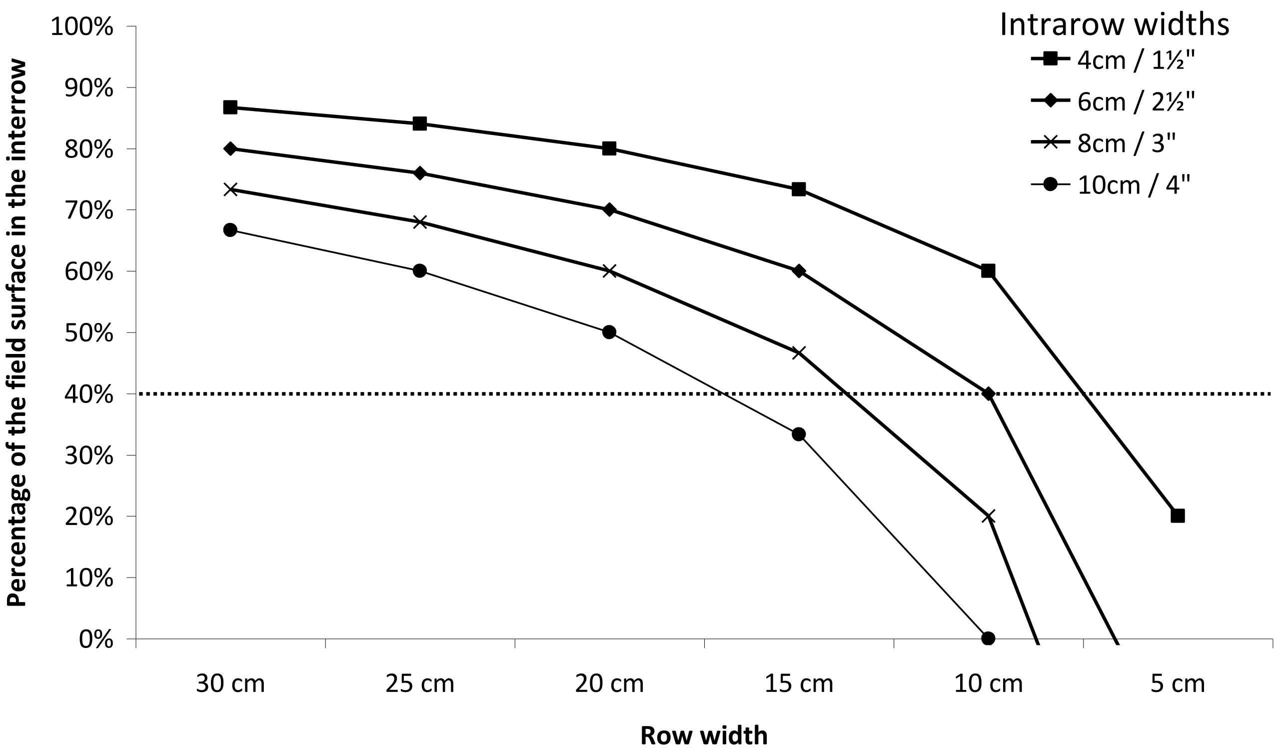

Figure 22. The percentage of field surface in the interrow for a range of row and intrarow / crop gap widths. The dashed horizontal line at 40% is the point where the value of interrow hoe's ability to aggressively weed the interrow starts to be lost and where contiguous weeders become a better option.

Figure 22 shows that at 40% of the field surface under the interrow:

- For a 4 cm / 1½" intrarow / crop gap the minimum viable row width is around 7 cm / 2½".
- For a 6 cm / 2½" intrarow / crop gap the minimum viable row width is around 10 cm / 4".
- For an 8 cm / 3" intrarow / crop gap the minimum viable row width is around 13 cm / 5".
- For a 10 cm / 4" intrarow / crop gap the minimum viable row width is around 17 cm / 6½".

The overall message is that the wider the crop row spacing and the narrower the intrarow / crop gap, the larger the proportion of the field in the interrow which can be hoed with aggressive interrow hoes, leading to better overall weed control.

5.14.10. Outside weeding frames / weeding tool widths

The outside weeding frames, or on smaller hoes, the outside weeding tools, needs to be ⅔ the width of inside weeding frames / weeding tool, to give the optimal overlap between bouts i.e., maximising the amount of overlap to minimise the chance of leaving an un hoed strip, while at the same time minimising the chance of hoeing / killing the outside crop row of the next-door bout. One of the key benefits of computer guidance systems is highly accurate bout-to-bout matching eliminating bout under and over matching.

5.15. Weeding tools

5.15.1. Key points

- Understanding the many different types of weeding tool and the design specifics of each is, essential for choosing the correct tool for a weeding job and ensuring their most effective use.
- Most weeding tools are based on horizontal steel blades that slice through the soil.
- Horizontal blades are subdivided into a three main types based on their shape: L T and A blade hoes along with ducksfoot / goose foot points.
- While they may appear superficially simple, there is considerable complexity in horizontal hoe blade designs, including multiple blades angles.
- L and T hoes are designed to weed next to the crop row. L hoes are the standard design, while T hoes are less common they have a number of advantages and are underutilised.
- A blade hoes along with ducksfoot / goosefoot points, aka sweeps, are designed to weed down the center of the interrow. The key difference between them is the pitch angle and therefore how much they dig into the soil and move soil sideways towards the crop row.
- Many weeding tools are used too deep, they should be targeting the weeds' hypocotyl and thus should only be deep enough in the soil so they can effectively cut the weeds.
- There are a range of non-blade weeding tools including, rotating spider hoes, mini-tine weeders and crumblers, designed to further break up soil and dislodge it from weed roots.
- Most row hoes (and other mechanical weeders) cannot work in high residues but can cope with low to medium amounts of residue. There are specific row hoe designs for high residue systems.
- Electrical interrow weeders have the potential to address issues such as weeding high residue systems, and killing larger weeds and weeding when the soil is too wet for mechanical weeding.

Changing the direction of travel, we will move from the weeding frame to the weeding tools, as working backward from those through the tool legs and springs and to the tool clamps will I hope provide a more logical explanation.

Weeding tools are where the rubber hits the road, or more accurately where the steel hits the soil. As discussed previously, modern row hoes are a 'Swiss army knife' platform for mounting an array of different weeding tools that can be swapped in and out to suit the crop, its growth stage, soil, and other variables, compared with older interrow hoes where the weeding tools were built into the weeder. As a result, there is a now a large variety of weeding tools available, with new approaches and variations on existing themes continuing to be developed. Choice of weeding tool is probably the most confusing aspect of row hoes for the newcomer. It is also a surprisingly technical area at times, so this is a substantial section.

The main approach of most weeding tools is broadly categorised into 1) horizontal blades, i.e., a piece of steel with a cutting edge exactly or mostly parallel to the soil surface, and 2) everything else.

5.15.2. Horizontal blade hoes

Horizontal blade hoes are sub-divided into three main types: L, T and A blade hoes (Figure 23). These names are based on the shape / profile of the blades. The L blade hoe looks like the letter L if viewed from the front or back, the T looks like a T when turned upside down, and the A blade is A or V shaped, when viewed looking down from above, depending on which way you are looking at it. Related to the A blade hoe is the ducksfoot or goose foot point (Figure 24). These have the same shape as the A blade hoe and a duck's / goose's foot, but, the defining difference is that an A blade will sit on a flat surface and the whole cutting edge will be in contact with the surface (as in Figure 23), while a ducksfoot only the tip / point is in contact when in a working position, i.e., they have pitch (Figures 24 & 25). The terms 'blade' and 'point' are therefore used in this report to differentiate between weeding tools with zero pitch = blades and non-zero pitch = points. Ducksfoot points are generally smaller than A blades, and they are also the same as the tillage points found on secondary tillage equipment. A blades and ducksfoots are also called sweeps, particularly in North America.

Figure 23. The three main types of horizontal hoe blades: L blade (left) T blade (center) A blade (right).

There is however, no agreement on the above names: ducksfoot, goose foot, A blade and sweep are common but often used interchangeably, L blade hoe is a standard name, but T blade hoe is not.

Figure 24. Ducksfoot / goose foot weeder blades which can also be tillage (cultivator) points.

5.15.2.1. Rake (α), sweep (γ), and pitch (ρ) angles

While appearing superficially simple, there is considerable depth to a well designed hoe blade (Figure 25). There are three critical angles for the horizontal cutting part of a hoe blade and point: rake (α), sweep (γ), and pitch (ρ) (Figure 25).

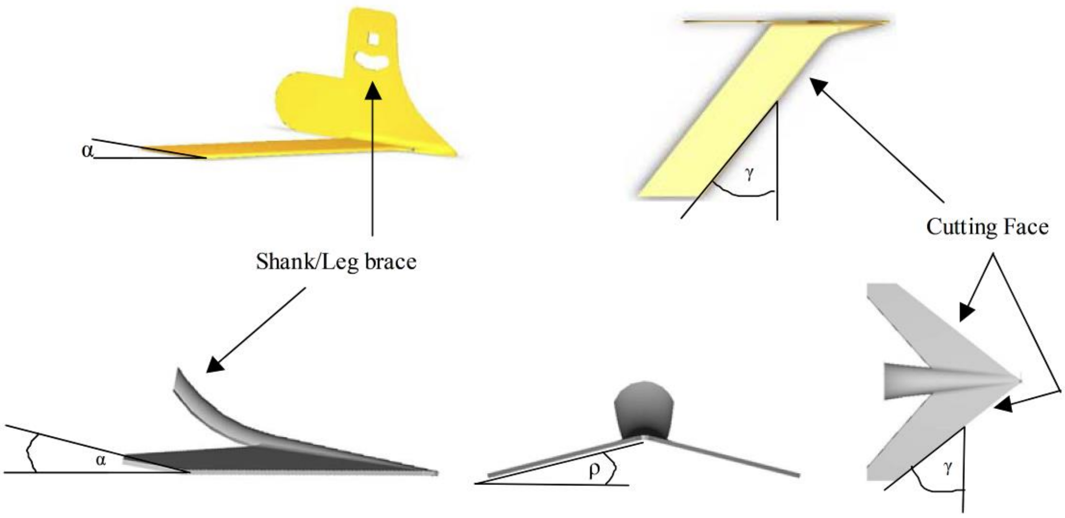

Figure 25. Hoe blade design. α = rake angle, γ = sweep angle, and ρ = pitch, from Welsh *et al.*, 2002; Home, 2003.

Rake (α, Figure 25, also called lift) is the angle that the blade makes with the horizontal in a vertical plane parallel to the direction of motion. A low rake angle will cause the blade to cut cleanly, with minimal soil disturbance. Increased rake angle generates more sideways soil movement and mixing of the soil whilst maintaining its cutting action. However, there needs to be sufficient rake angle e.g., >5° to crumble the soil flowing over the blade to break up the weeds' roots. Causing soil to effectively crumble, shatter and break up due to sufficient pitch angle considerably increases weed kill. Worse, if rake angle is zero the whole bottom of the blade scrubs on the soil, reducing the ability of the blade to cut into the soil, and it is more likely to bounce / roll along the surface. Rake angle is also responsible for the bottom of the cutting edge of the blade wearing and therefore maintaining sharpness and thus cutting ability. Having some rake angle is therefore essential.

Rake angle also differentiates, to some extent, between 'true' hoe blades and ducksfoot / goose foot points (see also pitch angle, below). True hoe blades typically have as small as possible rake angles, e.g., <10°. Ducksfoot points, including wide designs, typically have a larger rake angle, e.g., >20°.

Sweep (γ, Figure 25) is the angle of the cutting face or edge to a line perpendicular (at 90°) to the direction of travel. Sweep angle is critical for effectively slicing through weeds and clearing the blade of soil and residue. If the sweep angle were zero (Figure 26) this would be the same as a bed lifter / undercutter bar that is just pushing its way through the soil by brute force. When used at the soil surface, a zero sweep angle would rapidly pick up residue which will block the blade. Increasing sweep angles (Figure 26) increase the slicing effect of the blade so it more effectively cuts through weeds and residue, it also increases self cleaning as the soil and residue flows along the blade and reduces draft. However, too large a sweep angle reduces the cutting efficacy as the weeds are pushed to one side rather than cut. Also as sweep angle increases the horizontal width of soil that a blade of a given length weeds, decreases. So blades with large sweep angles have to be very long to achieve a small weeding width (Figure 26).

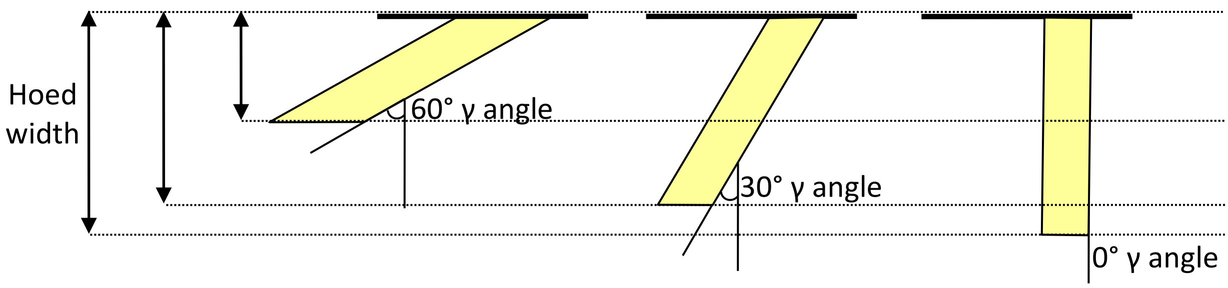

Figure 26. Change in horizontal weeded width, for the same blade length, as sweep (γ) angle on an L hoe changes.

In older L blade hoes such as in Figure 23 the sweep angle is around 60°. While this was optimal for the slow speeds of manually steered hoes, such large sweep angles in much faster computer guided hoes can result in too much sideways soil movement. Therefore L hoes designed for higher speed often have lower, e.g., 30°, sweep angles and they rely on the faster movement of soil over the blade to clear residue. Spring clamps (section 5.16), further assist with keeping the hoes clean by vibrating. Sweep angle is therefore a compromise, between self cleaning, effective cutting, draught and forward speed.

Pitch (ρ, Figure 25) angle only applies to hoes such as ducksfoots / goose foots where the front point is lower than the back end when in the operating position. Flat blades such as L T and A blades have zero pitch. All tillage points have a positive pitch. Pitch angle is what forces a hoe or tillage blade to dig into the soil in the absence of downforce. Pitch angle is thus another (somewhat fuzzy) dividing line between true hoe blades and tillage (cultivator) points that are also used for weeding. True hoe blades have zero pitch angle, their job is to slice through soil and weeds, downforce is applied by the weeder. Importantly zero pitch minimises the amount of soil moved sideways and also the vigour by which soil is moved - a true hoe blade will cause minimal sideways soil movement. Ducksfoot points /

shares have some pitch so they will dig themselves into the soil and by design they will move more soil, more vigorously, both sideways and vertically, than a true hoe blade.

Whether the extra soil movement of a ducksfoot is useful or a problem entirely depends on the context. However, where accurate soil movement into the crop row to bury weeds is required, mini-ridgers (section 5.19.3) are a better option due to their precise control of ridge height.

5.15.2.2. L blade hoe

L blade hoes are a traditional design and are still an important modern weeding tool — with some design changes to operate at greater speed. They are designed to work next / close to the crop row, particularly very small crop plants because a well designed L blade always moves soil away from the crop row. L blade hoes are thus handed, i.e., there are left and right blades for either side of the crop row, as per the center image in Figure 27 which has a pair of left and right hoes next to each other, on the left of the photo. On traditional interrow hoes, pairs of L blade hoes opposite each other on either side of the crop row were used as the guide to steer the hoe, i.e., the operator steered the hoe to keep the crop row exactly between a pair of L blade hoes.

In addition to above discussion of pitch, rake and sweep angles there are three other key design features of an L blade, the front point, the heal and the shank size (Figure 27).

Figure 27. L blade hoes with contrasting front points, heals and shank sizes. Left traditional Nicholson - Webb hoe, middle two generic hoes, right high speed hoe.

The front point can either cut upwards or cut downwards. Downwards cut is exemplified by the Nicholson-Webb hoe in Figure 27 with a long front point cutting downwards. The left hand hoe in the middle image of Figure 27 shows an upward cutting short front point. Slightly counter-intuitively downward cutting points are essential as any residue they encounter is either cut through as the front edge cuts into the soil or it is forced along the front edge of the blade. Upward cutting points, have nothing to cut against except the sky so they pick up residue that then collects on the leg, often leading to blockages.

The heal is the part of the shank behind where the back of the blade 'detaches' from the shank (Figures 25 and 27). The heal stops soil from falling into the crop row and burying the crop and killing it. Using the same two examples as for the front point, the Nicholson-Webb has a large heal that curves slightly away from the crop row / towards the blade, while the other hoe has no heal at all, rather a notch at the back of the blade. The Nicholson-Webb hoe with its large heal curving away from the crop row will stop any soil from getting into the crop row, while the other hoe drops a significant amount of soil into the crop row through the notch.

The size of the shank, both its height and length also determines how effective the blade is at keeping soil out of the crop row. Using the same two examples again (Figure 27) the Nicholson-Webb has a large shank both in height and length so it does not allow any soil to fall into the crop row, while the shank on the other blade is only large enough to attach it to the leg, and it allows a lot of soil to fall into the crop row. A tall shank also keeps the shank's joint with the leg and associated fasteners (nuts and bolts) further away from the soil so reducing the potential of crop and weed foliage and/or residue to get caught on them, causing blockages and crop damage.

One of the limitations of L blade hoes is that they need to be adjusted away from the crop as it grows, otherwise they will start cutting the crop's foliage (Figure 29). Adjusting hoes can be a time consuming and frustrating job, especially with older single locking clamps (section 5.17.2). Some newer hoes have systems for rapidly adjusting the lateral position of the weeding tool and/or weeding frame bars to quickly change the size of the crop gap, and/or better clamp designs make the task quicker and easier. Hydraulic width adjustment is also now available on a small range of row hoes which even allows on-the move crop gap adjustment from the tractor cab!

A further downside of needing to increase the crop gap for L blade hoes as the crop grows is that less soil in the crop row is weeded (Figure 29). This is a particular issue in transplanted vegetables which take some time to close the down-the-row crop gap, resulting in weeds in the intrarow-gaps between the crop plants not being controlled by either the L blade hoe or crop canopy closure.

5.15.2.3. T blade hoe

T blades hoes are uncommon, but, the concept has been around for many years (Figure 28). While there are only a few row hoe manufacturers supplying T hoes, they can be attached to any row hoe with suitable legs and clamps.

Figure 28. Three examples of T hoes. Left, on a manual intrarow weeder, center, Garford Farm Machinery's (garford.com) "Slasher hoe", right on pedestrian wheel hoe.

T hoes are used for the same purpose as L blade hoes - weeding next to the crop row, so they also have left and right hand versions. Their significant advantage compared with L blade hoes is that because the leg is in the center of the blade, the front of the blade can slide under crop plant foliage. For crops with spreading foliage, like carrots and lettuce, this means that a smaller crop gap is possible than an L blade hoe and also, as the crop plants grow, T hoes don't need to be adjusted away from the crop as much, so maintaining a smaller crop gap and maximising the width of the interrow (Figure 29). Less need for adjustment also means less time spent adjusting and more time weeding.

Like the L hoe, the T hoe is angled away from the crop row so it moves the soil away from the crop row, reducing the potential to bury crop plants. However, there is a small bow wave of soil around the tip of a T hoe, so there can be a small amount of soil movement into the crop row, which may bury newly emerged crop plants, particularly at faster speeds.

The T hoe is thus considered a valuable design that is under-utilised. They are also easy to build, as they are simply a piece of flat bar, cut on a 30° to 60° sweep angle, with a sharpened front edge, and then welded to a suitable leg at around 5° to 10° rake angle (Figure 23).

One possible reason they are uncommon is that as the tip of the blade is hidden under the soil, they cannot be used as a guide on manually steered hoes, in the way L blade hoes can. However, on computer guided hoes this is a complete non-issue, and for manually guided hoes, having a sight bar (section 5.23.3) is preferable than using pairs of hoes for guidance, so there is no reason T hoes cannot be used on manually steered hoes.

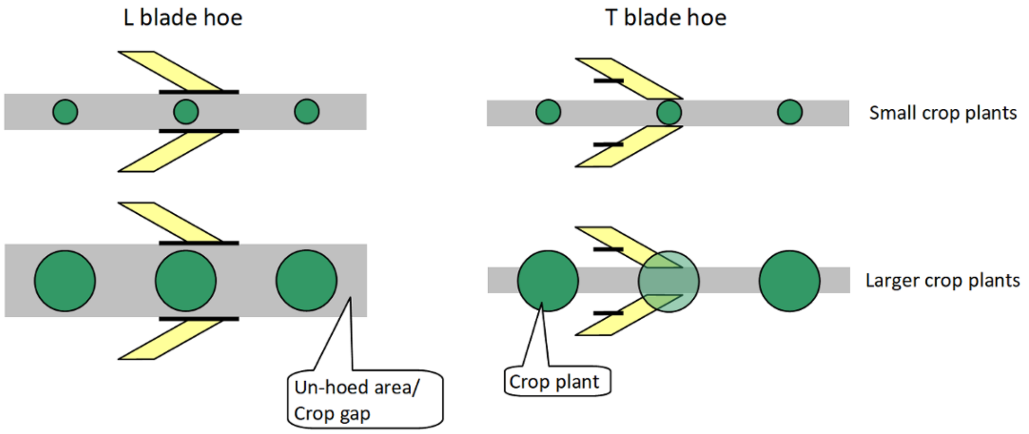

Figure 29. Comparison of L and T hoes' crop gap adjustment. The crop gap of L blade hoes needs to be larger than the width of the crop plants foliage so they don't damage them, so as the crop grows, the crop gap has to widen, increasing the area of un hoed soil. The tip of T hoes can slide underneath the crop, even at small crop plant sizes, so they minimise the un hoed area and the crop gap needs no or minimal increase as the crop grows.

5.15.2.4. A blade hoes and ducksfoot / goose foot points / sweeps

Being symmetrical, A blade hoes, ducksfoot points and sweeps move soil from their center line outward in both directions, while L and T hoes move soil in one direction only. A hoes and ducksfoot points are therefore not handed - there are no left and right versions. This also means that A hoes and ducksfoot points are generally not used next to the crop row, as there is the risk that the sideways moving soil will bury the crop plants when they are small. As noted above, where creating a precise ridge of soil in the intrarow is required, mini-ridgers (section 5.19.3) are the preferred tool. Larger A hoes are therefore typically placed in the center line of the interrow, often paired with L or T hoes next to the intrarow (Figure 30).

Figure 30. Classic arrangement of L blade hoes next to the intrarow / crop row and an A blade hoe in the center of the interrow.

For larger interrows, A hoes and ducksfoot points are often used in 'gangs' in a staggered pattern (the same way tines are arranged on tillage equipment) to minimise blockages and interference between neighbouring weeding tools (Figure 31). This is often preferable to having single larger A blades / ducksfeet / sweeps, for a range of reasons, such as better depth control, less force on individual tools and overlap so any piece of soil has two hoes pass through it, increasing soil mixing and weed kill (see below).

Figure 31. A blade hoes / ducksfeet arranged in staggered pattern. Right photo Horsch.com.

5.15.2.5. Electrical interrow weeders - a solution to the limitations of mechanical hoes?

Electrical weeding is a re-emerging technology that uses electricity to kill weeds (Merfield, 2024). This is either by heating the water in the weeds to boiling point (electrothermal) or disrupting the plants biochemical systems (electrobiological, Merfield, 2024). Interrow hoes using horizontal wire electrodes running just above the soil surface, perpendicular (at 90°) to the direction of travel, were developed in the 1980s (Merfield, 2024). A few companies are now developing modern electrical interrow weeders.

N.B. The terms interrow, intrarow and row hoe are used in this section quite specifically.

There is considered to be significant potential for electrical interrow hoes to address some of the limitations of mechanical interrow hoes. As the electrode does not touch the ground the issues associated with soil engaging weeding tools are avoided. Electrical interrow weeders should therefore be able to operate in high residue systems as the lack of soil contact will leave the residue undisturbed. Though for electrothermal systems, sparking causing the residue to catch fire is a demonstrated issue (Slaven *et al.*, 2023). The lack of soil contact would also be valuable where the soil is too wet for soil engaging tools. Plant death from electrical weeding is not dependent on the desiccating conditions that most mechanical weeding requires for maximum weed kill, so it would also be effective in colder wetter weather. It could also kill larger and tougher weeds or at least cause them considerably more damage than blades and points. Electrothermal also has lower energy use than many forms of mechanical weeding and electrobiological orders of magnitude less (Bloomer *et al.*, 2023; Merfield, 2024). As there is no soil engagement at all, and therefore virtually no draft (mechanical resistance) from the electrode (compared with hoe blades and points), it should be possible to build much lower weight machinery, i.e., interrow hoe toolbar and weeding units. Lighter weight would allow smaller tractors to be used and/or larger width machines for the same tractor power as soil engaging interrow hoes. The low power and weight requirements could also make electrical interrow weeding well suited to autonomous Level 1 robots (Merfield, 2023a), ideally solar powered, as some Level 3 (Merfield, 2023a) electrothermal robots already are.

A likely limitation of electrial interrow hoes is that forward speed will not be able to match that of mechanical interrow hoes, due to the need for the electrode to have sufficient contact time with the weeds and the mechanical dynamics of faster moving electrodes, particularly the popular thin finger flexible sheet electrode design (Merfield, 2024). This may be able to be offset by lighter weight and lower power requirements permitting wider machines. Further, it is considered unlikely that electricity could be used as a non-discriminatory intrarow weeder (section 5.18.2) as it not clear how the electricty could kill the weeds but not the crop. There are however already Level 3 /

discriminatory intrarow weeders using electricity to kill weeds, and it seems most likely that this is how electrical intrarow weeding can be achieved. It is therefore envisenged that interrow electrical weeders will be complimentary to mechanical row hoes, rather than replacements, and also complimentary to herbicides as well.

5.15.3. Weeding tool overlap

Where weeding tools are placed sequentially (one behind the other) particularly horizontal blade hoes (Figures 30 and 31) then it is essential to have some horizontal overlap of the blade positions. This is because weeds, particularly larger better rooted ones, will bend round the blade ends, i.e., weeds that only contact the blade close to the end won't be killed. A minimum of 5 cm / 2" horizontal overlap is typically required, with 10 cm / 4" a safer option. Best of all, having a full half tool width overlap means soil is hoed twice maximising weed kill (Figure 31). Putting extra weeding tools on a hoe is cheap compared to the cost of uncontrolled weeds. Don't skimp.

5.15.4. Deeper is not better — the importance of correct hoe depth

A common mistake is to weed too deep, particularly with knife blade hoes. Most weeds can only emerge from the top two to three centimetres / inch of soil (see Merfield (2018) for more information). This means their hypocotyls are at or very close, <1 cm / ½", to the soil surface. Most plants are killed outright if they are cut at the hypocotyl, particularly small weeds. Therefore, the correct target for hoe blades is the hypocotyl. Targeting the hypocotyl therefore requires hoeing as shallow as possible while still having the hoe deep enough that it remains just under the soil surface. Setting weeding tools deeper than this typically results in the weeds just being root-pruned, which they can potentially recover from. Hoeing too deep, especially with true hoe blades, also results in the soil sliding over the weeding tools in slabs (called 'slabbing'), rather than being broken up. This dramatically reduces weed mortality as the weed roots are not broken up as much and are attached to larger pieces of soil which have more water in them, so the weeds can regrow more easily. Slabbing can also damage crop plants. Further, running weeding tools deeper than 5 cm / 2" risks bringing up un-germinated, non-dormant weed seeds that then germinate among the crop (Merfield, 2018). Running tools deeper than necessary also increases draft and thus increases fuel use, thus running costs and also machinery wear. Therefore deeper is not better, it is worse — weeding tools, especially knife blade hoes, should be run as shallow as possible.

5.15.5. A fine even soil tilth will maximise weed kill

The need to have weeding tools running just below the soil surface also highlights the importance of a fine level tilth on the soil surface. Uneven ground, larger clods etc., will all significantly reduce the effectiveness of horizontal hoe blades. Having a fine, level tilth at the soil surface, i.e., < 3-4 cm / 1-1½", will considerably improve the effectiveness of all weeding tools. This is recognised as being contrary to the aims of reduced tillage, such as min-till and no-till. It is thus one of the many trade-offs in agriculture, increasing tillage to give a fine even soil surface is one compromise required to improve mechanical weed control.

5.15.6. Non-blade interrow weeding tools

While some form of horizontal steel blade dominates weeding tools there are other approaches. This section only covers interrow weeders, intrarow weeders are covered in section 5.18.

5.15.6.1. Rolling spider / star hoes / Lilliston rolling cultivator

The main non-blade option for interrow weeders are rolling spider / star hoes (Figure 32). These are all considered to be descendents from the original Lilliston rolling cultivator that was developed in the 1960s and is still available with improved designs (Figure 32).

Figure 32. Original Lilliston rolling cultivator (left), rolling spiders / star hoes (center, right).

Again there is no standard name for these tools, so spider hoe will be used, including for original Lilliston rolling cultivators. The defining features of spider hoes are the individual spoked wheels. The spokes are curved into a spiral around the axle, and also have either a twist in pressed sheet metal versions, or have once face angled in cast iron versions (Figure 32). Typically the spiders are used in 'gangs' either on a single or individual axles (Figure 32). The axle is offset to the direct of travel, which forces the spiders to rotate at a slower speed to forward speed, cutting and scuffing thought the soil.

The aggressiveness of the spiders, how much they penetrate the soil, the amount of mixing / churning, and how much the soil is moved sideways are determined by the offset of the spiders axle(s) to the direction of travel as well as the direction of the spokes' twist, and forward speed. Spider hoes are to an extent an extreme form of scalloped concave disk, which have a similar kind of action.

As they are a rotating tool they don't need to be kept at an exact angle relative to the soil, so they can be mounted on swing arms as well as parallelograms (Figure 33).

Figure 33. Parallelogram (left) and swinging arm (right) mounting of rolling spider hoes. Right photo Bigiron.com.

There are a number of pros and cons for spider hoes compared with horizontal blades, so only the key points will be discussed here. Compared with a horizontal blade of the same width a spider hoe is much heavier and has moving / wearing parts in the axle bearings. They also take up more space, especially when set up in gangs, so are better suited to wider row spacings, e.g., >40 cm / 16". Their working action is more 'diverse' than a blade, particularly being able to break up and crumble harder soil, and their churning and mixing action kills more weeds than simply cutting them. They can cope with moderate levels of residues and can have cleaner bars to stop longer stalks and leaves wrapping around the axles. They can also be used at higher speeds, though soil throw increases with increasing speed which may be an issue.

Depending on setup they will move soil sideways a little or a lot, which depending on objectives may or may not be beneficial. The sideways movement of soil and crumbling action means an important use for spider hoes is on ridge crops such as potatoes. Typically rolling spider hoes are therefore used as a dedicated setup rather than being mixed and matched with other weeding tools like L or T hoes mounted on a weeder frame. The exception is a ducksfoot or cultivator tine to break open the soil in front of the spider hoe.

There are a small number of manufactures offering rolling spider hoes, both in Europe and North America, with ongoing improvements including reliability, efficacy, ease of adjustment and overall usability.

5.15.6.2. Mini spring tine weeder

Mini spring tine weeders have a set of thin, spring tines for raking through the soil - i.e., a mini version of the contiguous spring-tine weeder (Figure 34, section 4.3).

Figure 34. Mini spring tine weeders that improve weed kill by loosening soil, knocking soil off weed roots and further breaking and burying weeds.

They are used as the last weeding tool on a weeding frame after the likes of L, Tend A blades. They further loosen and mix soil that has been hoed, breaking it up more, knocking more soil off weed roots, particularly larger weeds, breaking and burying smaller weeds and leveling off soil. This is another tool that was initially offered by only a small range of manufactures but is becoming widespread indicating it is improving overall weeding outcomes.

5.15.6.3. Crumbler

An alternative to the mini tine weeder are a range of crumbler type rollers which also aim to further mix and break up soil to improve weed kill (Figure 35). The benefits will depend on the exact design of the particular weeder and how it is configured. Compared with the mini-spring tine weeders a key design issue is that the tool rotates, potentially picking up residue and introduces a wear point at the bearing. These are offered by a few manufactures.

Figure 35. Rotating crumbling weeder tool. Photos Steketee.

5.15.7. High residue weeding tools

Most mechanical weeders (both incontiguous and contiguous) will only work in low to medium residue levels, or some only in residue free soil. This limits their use in conservation agriculture and reduced, minimum and no-till systems where retaining residue is a key objective. A few weeders can cope with large amounts of residue. Among contiguous weeders, the design of spoon weeders (section 4.3) inherently makes them able to cope with residue, and special high residue versions with wider spacing between the wheels, and knives to clean the spokes are available. Spring tine weeders, especially those with smaller angle or no bend in the tines can cope with moderate residue. For incontiguous weeders, most weeding tools on row hoes can only cope with small to moderate amounts of residue before they risk the weeding tools collecting sufficient residue they start to block. There are however interrow hoes that have been specifically designed to work in high residue levels. Typically these have a disk, or a depth wheel with a center cutting ridge, to cut through the residue which is then followed by a single large A blade hoe / sweep (Figure 36). An alternative is to have ducksfoot points on widely spaced S spring tines so residue can flow among them. High residue row hoes originate in, and are mostly used in North America, though they are starting to be built by European manufacturers.

Figure 36. High residue row hoe, with depth wheel incorporating a cutting disk which is followed by a single large A blade hoe.

As both mechanical weeding and retained residue systems both increase in importance it is expected (hoped) that new weeder designs that are better able to cope with larger amounts of residue will continue to be developed. Electrical interrow weeders may be a future solution to physically weeding high residue systems (section 5.15.2.5).

5.16. Weeding tool legs — rigid, sprung and e-springs

5.16.1. Key points

- The tool leg connects the weeding tool to the weeding frame. These are also surprisingly technical. Good design is key to their efficacy and ease of adjustment.
- There are both sprung and rigid legs.

There are three main types of legs / springs to connect the weeding tool to the weeding frame:

- Rigid leg,
- S spring tine,
- e-spring with rigid leg (Figure 37).

Figure 37. The three main weeding tool legs / springs. Left, fully rigid leg, middle, S spring tine, right e-spring with rigid leg.

Rigid legs (Figure 37) are simple and easy to make, so are the least expensive, but, if the weeding tool and/or leg hits a solid object something has to bend or break.

In comparison sprung legs can flex out the way of solid objects so reducing the chance of damage. More importantly they vibrate, even in soft soil conditions, which helps them cut through soil, plant stems and roots and more importantly keeps them clear of larger weeds, residues and stops soil sticking.

S spring tines (Figure 37) are typically exactly the same as those used on secondary tillage equipment. This means they are available everywhere and comparatively inexpensive. A key limitation is their individual height cannot be adjusted, so there is a risk that their depth is sub-optimal. They are mostly used for ducksfeet points as their depth is less critical.

e-springs clamps don't have an agreed name, but sticking with the alphabet based terminology for hoe blade designs, e-spring clamps are named after their shape, which looks like a lowercase 'e' with the exception of the final bend to form a clamp that holds the rigid leg (Figure 37). As per section 5.17.2, e-springs by their design lock each axis individually. They thus provide the best of all worlds: the advantages of being sprung, with both vertical and horizontal adjustment locked separately, making for easy and accurate adjustment, and the ability to mount any weeding tool. This has resulted in just a few manufacturers initially supplying them to them being used by nearly all manufacturers, indicating their considerable value. There are also increasing design variations, particularly the leg clamp. Early versions had a tendency for the vibrations to loosen the leg clamp bolt sufficiently that the leg would fall out. Many legs therefore have a pin or other device at their top to stop them dropping out should the bolt loosen.

All legs for A and T hoes should have a forward sweep at the base where they connect to the weeding tool (Figure 37). This is inherent in an S spring tine, but, has to be designed into rigid legs. The forward sweep moves the vertical part of the leg away from the soil and weeds flowing over the blade so reducing the potential for weeds and other residue to catch on the leg and build up. The T hoe on the pedestrian push hoe in Figure 28 shows an extreme forward sweep.

5.17. Weeding frame - weeding tool clamps

5.17.1. Key points

- It is surprising how the basic mechanical task of clamping two pieces of steel at right angles - the weeding tool leg to the weeding frame bar - can be done so badly, and to be done really well, requires excellent design.
- Vertical and horizontal adjustment should be locked individually.
- e-spring clamps inherently have independent axis locking.

Clamping the weeding tool leg or spring to the weeding frame bars may seem like a trivial design issue but for most row hoes this is the component that is adjusted the most often, and, thus poorly designed clamps are likely to be the biggest source of frustration and error when setting a hoe up. My dissatisfaction with poor clamp design over the decades has been so great that it led to me design a completely new clamp for rigid legs www.physicalweeding.com/merfclamp. A well designed clamp will therefore save many hours of time and much frustration when setting hoes up.

With the many different sizes / shapes of weeding frame bars, e.g., hollow section vs flat bar (section 5.14.2) and different weeder tool legs and springs it is not possible to give details of every particular design. The webpage for the 'Merf clamp' - listed above - has a detailed commentary on clamp design. So this is more general guidance about clamp design. This guidance also applies to older tool carriers with single weeding frames the height of which is manually controlled (section 6).

5.17.2. Individual or single lock for vertical and/or horizontal adjustment

One of the most important aspects of clamp design is whether both horizontal and vertical adjustment are locked off by a single bolt / locking mechanism or if horizontal and vertical adjustments have their own individual bolt / lock. The latter is infinitely more preferable. This is because often only one axis needs to adjusted, e.g., tool depth, but, if the locking mechanism locks both axes then the axis that does not need adjustment will become loose and may therefore may move as part of the adjustment process. Thus, getting both axes adjusted to the correct location and then locked in place with a single locking system can be both fiddly and frustrating. As noted above e-spring clamps by their nature have individual axis locking.

5.17.3. Ease of use / adjustment

The key questions to ask about any clamp are:

- Is it double or single axis locking?
- How quick and easy is it to accurately adjust?
- As the locking system is being tightened does the clamp stay in place or is it prone to move?
- How many and what tools are required, if any?

In older designs, clamps used standard bolts and nuts, so many required two tools, a socket and spanner to adjust. It is better if only one tool is required, or best if there is toolless adjustment. Ideally everything on a weeder, e.g., weeding frame and toolbar clamps, parallelogram springs, etc., uses the same bolt head size, e.g., 19 mm / ½", so that only one spanner, socket, etc., is required to adjust everything on a hoe. Further, how easy are the adjustment points to reach - are they easily accessible from the top and rear of the weeder, or do you have to get between the tractor and the weeder, or reach underneath parts to access adjustment points? Cordless / battery powered impact drivers can make adjustments much faster and easier.

5.18. Intrarow weeding tools

5.18.1. Key points

- Intrarow weeding tools are divided into two types: 1. discriminatory / high tech and 2. non-discriminatory / low tech.
- Discriminatory weeder systems are mostly computer vision system based, they are therefore complex and often built as a single machine, with interrow weeding systems integrated into them. They are therefore outside the scope of this report.
- Non-discriminatory weeders are simple mechanical (low-tech) tools with a diverse range of highly effective weeding actions.

- There are now sufficient types of non-discriminatory intrarow weeders that fit onto row hoes that exceptional whole-of-field weed management using only row hoes is now a reality.
- Before buying into the cost and complexity of discriminatory weeders, it is strongly recommended that non-discriminatory weeders on row hoes should be tried first until it is proven they can't achieve good enough weed management, and thus a discriminatory weeder is justified.
- The main intrarow weeders are in order of importance / common use: finger weeders, mini-ridgers, concave disks and ridgers, torsion weeders and rotating vertical wire weeders.
- Most of the intrarow weeders are highly complimentary and will achieve the best overall weed management when used in combination / sequences.

As previously discussed, older interrow hoes, where the weeding tools are part of the whole machine, have evolved into row hoes which are a platform for mounting a diverse range of weeding tools, both interrow and intrarow. The introduction of intrarow weeding tools is thus considered a key point in the transition from interrow hoes to row hoes. Prior to that intrarow hoeing was done by manual labour with hand hoes. The phrase "a tough row to hoe" originally was no metaphor — it meant exactly what it said — a crop row full of weeds that was hard work to manually hand hoe. Intrarow weeders have thus been truly game changing, vast hours of very tedious, back breaking, manual work have been eliminated by them.

5.18.2. Non-discriminatory vs. discriminatory — low tech beats high tech!

As briefly discussed in section 4.6 intrarow weeding tools are sub-divided into discriminatory and non-discriminatory approaches. In the former, typically a computer vision system identifies the location of each crop plant and weeds around it (Figure 38).

Figure 38. A range of discriminatory intrarow weeders (which include interrow weeding tools). Left photo FerrariGrowtech.com Removeed, center photo Lemken.com IC-Weeder AI, right photo Garford.com Robocrop in-crop weeder.

In the latter the weeding tool acts on crop and weeds alike and relies on the crop being tougher / more resistant to the weeding action to survive while the weaker weeds are killed. Discriminatory intrarow weeding is therefore typically a high-tech technique, while non-discriminatory intrarow weeders are mostly low tech, i.e., mechanical.

5.18.2.1. Close-to-crop plant weeds — the Achilles heel of discriminatory weeders

A critical limitation of most discriminatory weeders is that they have to avoid weeding a small area directly around the crop plant — the close-to-crop plant area — otherwise they risk damaging or worse, killing crop plants. This is because their weeding technique is lethal to crop and weeds alike, hence why they need to discriminate crop plant from weeds. This is particularly true of weeders that use articulated hoes that move in and out of the crop row weeding around crop plants, while it is the least true of lasers and other systems that impact very small areas of, e.g., < 1 cm^2 / < ¼ square inch, with little or no soil disturbance. In contrast, as non-discriminatory weeders weed the crop and weeds alike, their mode of action means they have to weed close-to-crop plant weeds.

The need to leave a safe zone around crop plants is a particular challenge for discriminatory weeders as it is the close-to-crop plant weeds that are the biggest problem. Weeds growing in the middle of the interrow, or half way down the row between vegetable transplants are unlikely to compete with the crop until both are well grown, and are most likely beyond the critical period of weed control[2]. Conversely it is the weeds growing right next to the crop plant — close-to-crop plant weeds — that are going to compete with the crop plants from pretty much day one. Thus, ironically the most expensive, highest tech discriminatory weeding machines cannot kill the most important weeds in the field — the close-to-crop plant weeds — which the simpler weeding technology - non-discriminatory intrarow weeders - can!

5.18.2.2. Other limitations of high-tech discriminatory weeders

With the exception of the highest precision discriminatory weeders, such as laser systems, there needs to be sufficient space between crop plants for the intrarow weeding tool to work. This means that more closely spaced crops, including arable crops such as wheat, maize (corn), e.g., cannot be weeded with discriminatory weeders as they cannot weed between the crop plants. Further, many discriminatory weeders typically have slow forward speeds, as their weeding mechanisms, e.g., articulated hoes, spot spraying, lasers, etc., cannot work at faster speeds, e.g., hoes can't move in and out of the row fast enough. The computer vision systems can work at higher forward speeds, often much higher speeds, rather it is the weeding method that is the speed limiting factor.

In addition, for discriminatory weeders killing individual weed plants, e.g., using spot spraying and lasers (compared with articulated hoes, which weed the soil not individual plants), the number of weeds affects forward speed, i.e., if there are lots of weeds the forward speed has to be reduced to allow the weed killing method time to kill every weed. Thus even more ironically, such weeders need to be used in the most weed-free fields possible to maximise their work rate, so they are best used after the crop has been extensively row hoed, or weeds controlled by other means, e.g., herbicides This means that most discriminatory weeders operate at a slow walking pace, and a fast walk at best. In comparison row hoes using both interrow and intrarow weeding tools can operate at considerable speed, especially with automatic guidance systems. Forward speeds of 10 kph / 6 mph are common with over 20 kph / 12 mph possible in the right conditions. These speeds coupled with the large widths of row hoes means that row hoes with non-discriminatory intrarow weeders can thus achieve vastly higher work rates, at much lower overall cost, with as good, if not better weed control, than discriminatory weeders.

Finally due to the complexity of discriminatory weeders, there are far fewer companies making them compared with row hoes. They also tend to be integrated (Figure 38) rather than modular, so are setup for particular row spacings and crop types, making them less flexible. Many use hoods / shrouds for the camera systems (Figure 38), again limited flexibility, and the current maximum width is three vegetable beds / <6 m / yards, compared with 30m / yards for the biggest row hoes.

5.18.2.3. Low tech beats high tech!

The key message is that low-tech, non-discriminatory, intrarow weeders on row hoes should be tried to failure before even considering investing in expensive, high-tech discriminatory weeders. In short:

"Low tech beats high tech"

This report therefore focuses on low-tech, non-discriminatory intrarow weeding tools that can be used on modular row hoes, which despite being low-tech can be very effective. There is also a growing range of intrarow weeding tools, so only the most common / important ones are covered here.

[2] https://extension.sdstate.edu/critical-period-weed-control-good-not-perfect-guideline

5.19. Non-discriminatory intrarow weeders

5.19.1. The crop must be tougher than the weeds

Reiterating the comments above, for non-discriminatory intrarow weeders to be effective the crop must be considerably more resistant than the weeds to the tools' weeding action. Typically this means transplanted vegetables and larger seeded deeper planted arable crops. Though direct sown vegetables e.g., onions, when they are larger, can also be weeded. If there is not enough difference in susceptibility between crop and weeds the crop will be harmed, even completely killed. It is therefore possible to make some very costly mistakes with non-discriminatory intrarow weeders, so, taking time to fully understand them and to correctly set them up, is time well spent.

5.19.2. Finger weeders

Finger weeders are the most common intrarow weeder. Developed in the 1950s in the USA by the Buddingh Weeder Co, while effective the design had some issues. They were then separately re-designed in the mid 1990s by K.U.L.T. - Kress and Steketee who both patented their designs. The two companies then reached an agreement and worked together on what is now called the 'sandwich design'.

The sandwich design finger weeder has a (typically) metal disk with bent prongs called the drive plate sandwiched to a flat finger disk, both of which are in turn mounted on a bearing / hub and then on a leg (Figure 39). While the sandwich design is the most common design, single piece injection moulded forms and other variations are also produced (Figure 39).

Figure 39. Sandwich design and injection moulded finger weeders.

They work by the prongs on the drive plate digging into the soil and making the weeder rotate. The fingers then work the soil in the intrarow, moving and scuffing it around thus killing small weeds but leaving larger, better rooted crop plants intact. Typically they are used in pairs opposite each other on either side of the row, so that the action of one weeder interacts with the second of the pair, increasing the weeding effect.

Their popularity is partly due to their flexibility. The size / diameter varies from as small as 20 cm / 8" for narrow crop rows, to half a meter / yard wide for perennial crops such as grapes. The material that the weeding fingers are made from vary from the very hard and inflexible, such as steel, through various types of plastic, to flexible reinforced rubber, and finally to very flexible brushes. The weeding action thus varies from highly aggressive to very gentle. This means that there is a design to suit pretty much every intrarow weeding situation. The design is also mechanically simple, with only one moving / wearing part, the bearing.

As the weeder heads are round and rotate their weeding action is less sensitive to forwards and backwards pitch (angle), unlike hoe blades, which have to be kept exactly horizontal to achieve the correct weeding action. This means finger weeders can be mounted on swing arms rather than parallelograms, though they are also directly mounted on parallelogram weeding frames as well (Figure 40). They are also reasonably tolerant of adjustment accuracy, with the change in the level of weeding action relatively small for relatively large changes in adjustment. This makes them easier to setup as they don't require such fine and accurate setting as some other tools. Being flexible also means that achieving the optimum setting can take a bit of trial and error.

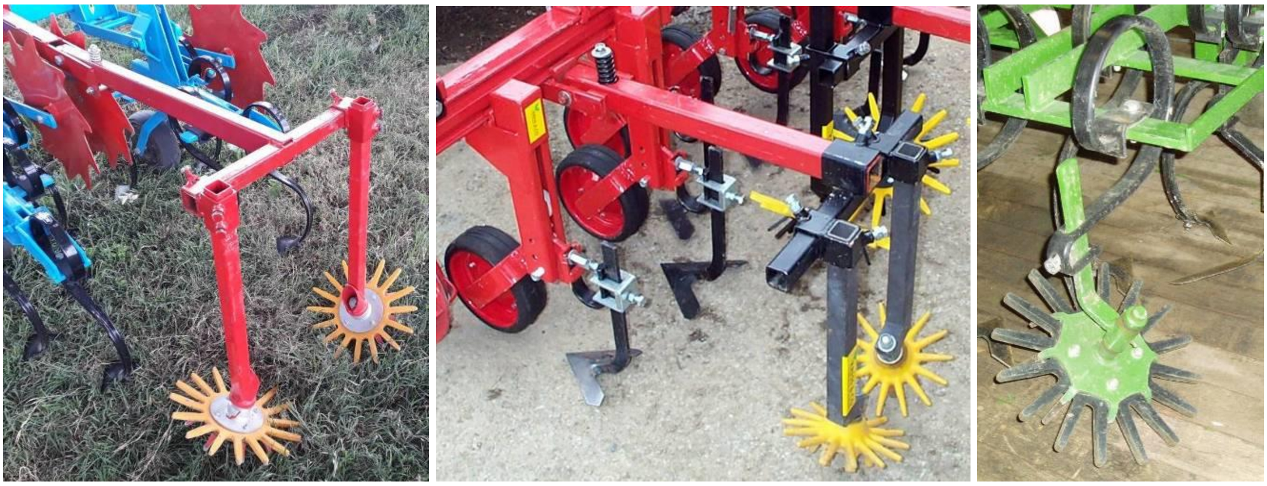

Figure 40. Finger weeder, mounting systems: left and center images, spring tensioned, swing arm, mounting systems; right image, weeding frame mounting on an e-spring clamp.

Changing the size of the gap between pairs of weeders changes the intensity. Having the fingers overlap will increase soil movement and weeding effect, while moving them apart, or staggering them, reduces soil movement and aggressiveness. A faster forward speed increases the intensity with more soil movement and thus aggressiveness of the weeding action.

Newer finger weeder designs have introduced the ability to change the weeder head angle front to back which changes how the tool moves soil into or away from the row, so they produce more of a ridge or pull soil out of the row (Parks & Gallandt, 2023). Side to side angle adjustments are also available on a few finger weeders.

Finger weeder effectiveness depends on soil and weather conditions because the weeding action is less aggressive, so fewer weeds are directly killed by the weeding action, more will be partly uprooted, dislodged etc., so may survive in cool moist conditions but be killed in hot dry conditions. They also need a reasonably fine tilth, and will not be as effective in cloddy conditions. They also loose efficacy in stony soils, though, are mostly unharmed by them.

5.19.3. Mini-ridgers

Mini-ridgers work by creating a ridge of soil in the crop row, from as small as 1 cm / ½” to around 10 cm / 4” high, burying weeds but leaving the crop protruding from the ridge. If the soil ridge overtops the weeds by 1 cm / ½” then close to 100% weed kill is achieved. This is regardless of weed height, even tall weeds, e.g., 10 cm / 4” are as susceptible as newly emerged cotyledon stage weeds. If 2 cm / 1” of the crop, regardless of its height, overtops the ridge then survival is close to 100%. Thus is there is a 3 cm / 1 ½” height differential between the crop and weeds, close to 100% weed kill can be achieved with 100% crop survival (Merfield, 2014; Merfield, 2018). Even if weeds are not fully covered by 1 cm / ½” of soil, a significant number will still be killed, and more dead weeds are better than less!

Mini-ridgers are also unusual among mechanical weeders in that most weeders kill by a mixture of severing, uprooting and burial, with efficacy maximised in hot dry conditions that desiccates weed that are not directly killed, e.g., only uprooted (section 5.15.2.1). Mini-ridgers work entirely by burial, i.e., starving the weeds of light, so as long as the soil is not so wet and sticky that a good ridge cannot be formed, they will achieve the same level of weed kill in hot dry conditions as wet cold conditions, even rain. As stonyness and cloddiness increases it means that there are more gaps between stones for weeds to survive in, but the ridgers themselves can cope with very stony conditions.

Mini-ridgers have been re-invented on multiple occasions. They are one of those approaches that are obvious with hindsight but take considerable foresight to conceive of! The best design is also the simplest. Two pieces of flat bar are welded on their cut edges to make a V shape, between 90° and 45°C with a vertical (flat face) and then attached to a leg (Figure 41). In effect they have a 90° rake angle (5.15.2) which is why they move soil sideways. Mini-ridgers are designed to run down the middle of the intrarow and push soil into the two adjacent crop rows. Single sided versions are designed for wide and outside rows (Figure 41). Alternatives have the horizontal bars mounted behind A blade hoes, with width adjustment systems, sprung / floating and other variations (Figure 41).

Figure 41. A diverse range of mini-ridger designs.

With the basic design, the height of the ridge can be precisely controlled by using different height bars. This is because soil is pushed along the front face, and excess soil flows over the top of the blade, so only soil moving along the front face ends up in the ridge, which thus is the same height as the bar height. This does entail having multiple sets of mini-ridgers of different heights but considering how simple and cheap they are this is not considered a barrier to their use.

Where higher forward speeds are used the size of the angle between the two blades is reduced from the standard 90° to as narrow as 45°, center top photo in Figure 41, left most ridger. This moves soil sideways more slowly, minimising uncontrolled soil throw, but requires longer blades, the same as for L blade hoes (Figure 29).

Only a few manufacturers offer mini-ridgers, but, they are very simple to build, the legs can be manufactured to fit into an weeder's existing clamps, they can be fabricated on farm or at a local agricultural machinery engineer / mechanic so can easily be retro-fitted to existing hoes.

5.19.4. Concave disks, rotating spider hoes and ridgers for hilling

When crops are sufficiently large, e.g., > 20 cm / 8" small concave disks or rotating spider hoes (section 5.15.6.1) are better to hill soil in the row (Figure 42) instead of mini-ridgers which are less effective at creating larger ridges. This is both for crops grown on the flat to make a new ridge and to build up / maintain crops grown on ridges. Disk sizes vary to match the task. Concave disks can also used as crop protectors when run straight (section 5.21 below).

Figure 42. Small concave disks being used for ridging (left) fixed ridger (right).

An alternative to disks are fixed ridgers (Figure 42) which are basically scaled down potato ridgers. The same pros and cons apply to these smaller disks and fixed ridgers as their larger counterparts. Disks are less prone to clogging, especially in wet soils, but, have bearings that need lubrication and wear out, while fixed ridgers can suffer from soil adhesion and residue build-up but, don't have any moving parts.

5.19.5. Torsion weeders

Torsion weeders were another tool originating in the USA that have spawned a wide range of variations on the original concept. They consist of flexible / spring steel bar / rod that varies from quite thick e.g., 1 cm / ⅜" and rigid to thin e.g., 3 mm / ⅛" and highly flexible (Figure 43). They are typically used in pairs either side of the crop row to break up and mix the soil in the intrarow killing small weeds.

Figure 43. A range of torsion weeders.

The newer, more flexible torsion weeders where the ends are parallel with the soil surface and pointing towards the crop row appear to gaining in popularity and are complimentary to finger weeders and mini-ridgers. Larger stones will deflect the ends of torsion weeders reducing weed kill but won't damage them.

5.19.6. Rotating spring wire weeders

Rotating vertical spring wire weeders pass a series of thin (~4 mm / ⅛") vertical, sprung, wire tines through the intrarow scraping and scuffling out the weeds. The most common form has the tines on a wheel which is offset to the direction of travel so it turns more slowly than forward speed, so sweeping through the intrarow Figure 44.


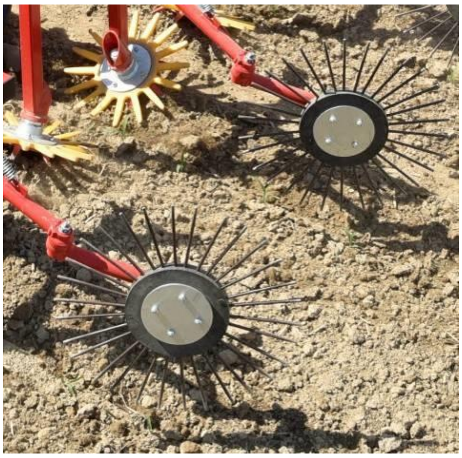

Figure 44. Rotary vertical spring tine intrarow weeders. Left photo Steketee, right photo Einböck.

Vertical wire weeders work exceptionally well with thin vertical crops, such as maize / corn, onions and leeks, but they can damage more leafy spreading crops e.g., soybean, lettuce. Even in well suited crops they are quite an aggressive tool so need to be setup and used with care, i.e., slowly. While they will work in stony soils there is risk of crop damage with stones being moved around.

5.19.7. 'Stacking' intrarow weeders for best overall weed management

The above non-discriminatory intrarow weeders are highly complimentary in their working actions, such that to achieve the best overall weeding results they should to be used both together at the same time and in sequence. The most obvious pairings, are the mini-ridger with finger weeders and vertical wire weeders, the former creates a small ridge which the latter then pull down at a later date, with weed kill achieved on both passes. Torsion weeders can be used before or after finger weeders and vertical wire weeders, and can run along the tops of larger ridges right next to the crop row where other tools like finger weeders may struggle to get sufficient traction. Therefore, having more rather than less intrarow weeders at your disposal will maximise your ability to kill intrarow weeds in a wider range of soil and weather conditions. More information on intrarow weeders, particularly mini-ridgers, can be found in Merfield (2014, 2018).

5.20. A word on speed

With computer guidance systems the forward speed of a row hoe is only limited by the movement of soil through the weeding tools and tractor stability (bounce). The computer guidance systems themselves could work at speeds far faster than is practical or safe for tractors and equipment.

Weed management, both herbicide and mechanical, are often time critical operations - there is often a lot of crop to weed all at the same time, within constrained weather windows. Therefore operating a row hoe as fast as possible is often essential. The key issue with increasing speed is increased soil movement, i.e., throw. A weeding tool operating at walking speed may not throw any soil into the crop, while at faster speeds, considerable amounts of soil may be thrown into the row. The amount of soil throw for any specific weeding tool varies considerably among different designs, i.e., there are different high and low speed designs. Therefore, when selecting weeding tools, the target working speed must be taken into consideration, and when testing setups, tools need to be tested at their working speeds (section 5.22.4). Crop protection systems (section 5.21) may be optional at low speeds but essential at higher speeds.

The draft of all soil engaging tools, both tillage and hoes, increases exponentially with forward speed. However, for most row hoes using true hoe blades draft is very small to start with so the increase in draft with increasing speed is a minor issue. For roe hoes using deeper working ducksfoot points draft at higher speeds can be an issue, particularly increasing bending of spring tines.

5.21. Crop protection systems

5.21.1. Key points

- Small crop plants are at risk of being buried and killed under soil flowing off weeding tools.
- Crop protection systems keep soil out of the intrarow, protecting small crop plants, and larger vegetables from soil contamination.

Small crop plants, particularly direct drilled vegetables, can be buried and killed by soil from weeding tools. Larger vegetables, e.g., lettuces, can be contaminated by soil thrown into the leaves. This is particularly the case with ducksfoot points and a lesser degrees A blades, to a lesser extent still with T blade hoes and the lowest extent with well designed L blade hoes, the latter being designed to minimise soil movement into the rows (section 5.14.9). Where there is a risk of pushing soil into the intrarow and harming the crop, there are a range of crop protection systems to keep soil out of the crop row. These are mostly either rotating disks or floating shields.

Rotating disks come in two forms, rolling and cutting (Figure 45).

Figure 45. Disk crop protectors. Left and center rolling / walking disks and right concave cutting disks.

The rolling / walking type are larger diameter with a slight depression for strength, with teeth / serrations around their edge and are designed to roll / 'walk' along the ground at forward speed (Figure 45). These are typically used in crops with upright growth forms like maize, rather than crops with foliage than spread sideways, like carrots. Cutting disks (Figure 45) are smaller, have a smooth edge and are concave so they cut soil away from the intrarow. They tend to be used more as a weeding tool in their own right, to weed close to the crop, but, they are also used to protect the crop from soil thrown by other weeding tools, either when cutting soil away from the intrarow or running parallel to the intrarow so they just roll along, like the larger walking disks. Again, cutting disks cannot be used in crops with spreading foliage, like carrot, as they will cut the foliage off. For these kinds of crops floating shields are required. Floating shields are typically mounted on a horizontal parallelogram to allow them to follow the soil surface, while still cutting into the surface to fully block sideways soil movement (Figure 46). They have an upswept leading edge, or at least partly upswept, so that they gather spreading crop foliage and fold it between the two shields (Figure 46).

Figure 46. Floating shield type crop protectors, with upswept leading edges to gather and fold crop foliage between pairs of shields.

5.22. The critical importance of accurate and precise setup of drills, planters and row hoes

5.22.1. Key points

- It is essential that all row-equipment: drill, planter and row hoe are set up to exactly the same spacings.
- With the exceptional accuracy of computer guidance and many manual steering systems all machines need to be setup with high levels of accuracy and precision.
- Using jigs, marker bars, and similar techniques helps achieve the require accuracy and precision with the least amount of in-field setup.
- Once in-field, final tweaking of setup will be required due to differences in soil and crop.
- Once operating, constant vigilance is the watchword of the row hoer.

As discussed in section 5.3 all equipment used for row-crop work, the drill, planter and row hoe must be accurately and precisely setup on exactly the same, and symmetrical, row spacings.

5.22.2. Chalk it up for starters - figuring out what weeding tools to use

The range of permutations of weeding units, weeding frame designs, weeding tools etc., and how they relate to each other on a weeder, can all be highly confusing, especially to the newcomer. A good starting point to help get your head around them all, is to mark out your crop row lines on a concrete floor (e.g., using chalk, masking tape, etc.) including the size of the crop gap, then get a sample of the individual weeding tools you are considering using, and place them on the floor to see how they look, including achieving sufficient overlap for tools front to back and sufficient side to side clearance to avoid interference between tools.

5.22.3. Ex-field hoe setup, jigs and guides

With the level of accuracy now possible with computer guidance systems, setting up row hoes in the field using the crop rows as a guide, is challenging at best, and a fools errand at worst. Using setup jigs in the yard or the workshop (undercover) to make sure **all** equipment is correctly setup before being taken to the field, is hugely valuable. For example, Figure 47 shows three jigs for setting up a three meter wide row hoe with wide, medium and narrow crop gaps. The same is true for the drill or planter, having a fixed guide, e.g., wooden batten or steel bar, with the crop rows marked on / cut into it, is much easier and more accurate means of checking drill points than a tape measure. Some growers have gone to the effort of creating perfectly flat concrete pads with crop row markers of various widths made of steel, embedded into the concrete to ensure the best possible drill and hoe setup!

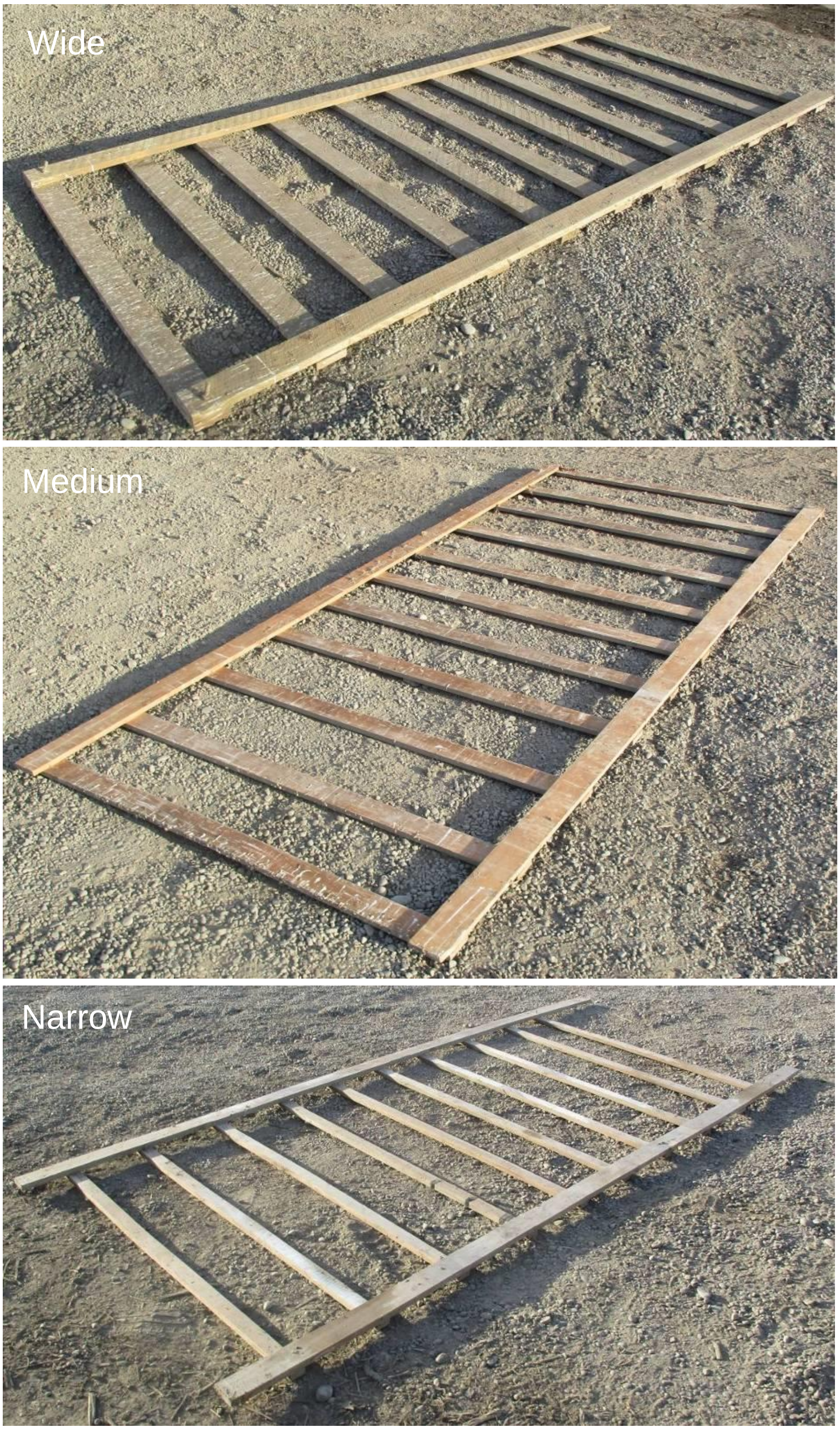

Figure 47. Wooden jigs for setting for setting up a three meter wide row hoe, on 30 cm / 12” wide interrows (crop rows), with wide, medium and narrow intrarow spacings.

It is also essential to check the spacing at the drill / planter points / coulters and weeder tools at the location where they engage with the soil, rather than just running a tape measure across the toolbar. There may be bends, manufacturing imperfections, loose / worn joints etc., that mean that even though everything on the toolbar is spaced perfectly, that may not be true where the steel hits the field. Using jigs and guides also helps check for tool rigidity. For highly accurate work, there must be the minimum, e.g., a few millimetres / ⅛" sideways movement of drill coulters and weeding tools. Where there is more movement, this indicates that the joints and various moving parts need to be tightened, greased and/or replaced.

The more time spent in the yard or shed setting up the drill, planter and weeder, with access to tools, good lighting, warm dry conditions, coffee, etc. will save multiples of that time adjusting the weeder in the field, often in much less pleasant conditions.

5.22.4. In-field hoe setup: Test, tune, rinse, repeat and constant vigilance

Having undertaken ex-field hoe setup (described above) some final in-field adjustments are still likely to be required as ex-field setup can't anticipate variables such as how hard or soft the soil is, crop growth stages, weed species, populations and sizes, weather conditions etc. The hoe needs to be run down a short length, e.g., 10 to 20 meters / yards of crop that is representative of the wider field, e.g., avoid the first rows along the fence. Then get off the tractor and check the results. It is impossible to tell if the right outcome is achieved from the tractor, you **must** get down and hand-pull weeds and crop alike to check the former are loose and the latter still rooted. Having two or more people on this job, one in the tractor and the other(s) walking behind the hoe to check the hoe in operation can be hugely valuable and use less person-hours in total, as it reduces the amount of jumping in and out of the cab. It also allows the hoe to be checked when it is working, which allows for easier identification of issues such as soil flowing poorly through weeding tools.

The most important check is: are the weeding tools next to crop row in the right place? Key is that they are not harming crop plants, e.g., burying, cutting, uprooting, etc. Test by pulling on some crop plants to ensure they are still firmly rooted, especially when using intrarow tools that directly impact the crop plants, like finger weeders. Then, ask the opposite question: could those next-to-crop-row and intrarow tools be moved any closer to the crop row to kill more weeds without harming the crop?

If crop protection devices are being used (section 5.20) are they functioning correctly, i.e., keeping soil out of the crop row and at the best distance from the crop row? Next check that soil and weeds are effectively flowing through all the tools? Or are some too close to each other and therefore going to block up? Do they need to be moved to another location on the weeding frame? Then, are there any strips in the interrow that are not being weeded effectively? Are more weeding tools required to cover those missed strips or can existing tools be moved to weed the gaps?

Finally check all weeding tools are at the optimal depth by inspecting the damage they have done to the weeds. Have they cut them off cleanly, as close to the hypocotyl as possible? (section 5.15.3). If not then adjust the height of the whole weeding frame via the depth wheel and/or the height of individual tools until they are all at the optimum depth.

Then once the initial adjustments have been made, test the new setup, by hoeing another few tens of meters / yards and then rechecking that everything is working optimally. It may take several repetitions of adjust - check - readjust to get the hoe working perfectly.

This includes using the hoe at the optimum / fastest speed possible (section 5.20). Don't just test the hoe at a slow speed and use it at a faster speed. As tool alignment is optimised, it needs to be tested at working speeds, as soil throw will increase, tool actions may vary etc. So, the final testing runs must be done at operating speed over a good length of row, e.g., 50 m / yards.

Once the initial setup has been completed and the hoe appears to be working well, it is **not** time to rest on your laurels. Changes in field conditions, e.g., varying soil texture across a field, the day warming up and drying the soil surface out, all mean that on a regular basis the efficacy of the hoe needs to be checked by getting off the tractor and seeing what it is doing to crop, weeds and soil. Even with the many advanced features on 2nd Generation row hoes, experienced farmers and growers will still frequently check that the hoe's performance and fine-tune as necessary. A useful tip is to check the next door bout just after turning into a new row to save walking round the back of the hoe.

It is also vitally important to keep visually checking the hoe during operation. In good conditions with friable soil, good weather and small weeds, a hoe will work flawlessly. However, in sub-optimal conditions, such as the soil being on the sticky side, larger weeds > 10 cm / 4" high, bigger weed populations, residue, hitting hidden objects like bricks, etc. there is increased risk of blockages and other failures that risk the crop being harmed even killed or weeding failing to be effective. Finally there is human error: for example a weeding tool was not tightened sufficiently, becomes loose and slowly moves into the crop row and starts killing the crop. Thus:

Constant vigilance is the watchword of the row hoer.

5.23. Guidance systems

5.23.1. Key points

- Computer guidance systems based on either RTK GPS or computer vision systems have revolutionised interrow hoeing.
- Nearly all guidance systems are now vision systems indicating they have an overall advantage.
- Coupling the now common RKT GPS tractor autosteer with vision guidance on the row hoe is a dream-combination.
- There are both old and new low-tech guidance systems such as sensor wands that are still good options in the right situation.
- Manual guidance is still viable and is the common approach on small farms.

Computer guidance systems, both RTK GPS and vision were revolutionary for interrow hoeing. They turned what was a specialised job, requiring an extra worker for manual steering, or using purpose designed tool carrier tractors, requiring super-human levels of concentration and driving skill, into a standard three-point-linkage tractor job. With the first computer guidance systems coming to market nearly three decades ago, they are now a mature technology, with many manufacturers offering them as a turn-key package with their weeders.

Vision systems use one or more digital cameras pointing at the crop rows and then the software identifies the location of the crop rows and adjusts the lateral position of the row hoe to keep it on track. GPS systems are based on tractor autosteer and more recently implement steering, also called 'double-steer'. Most computer guidance systems for row hoes are based on vision, only a small number are now purely GPS based.

5.23.2. RTK GPS guidance systems

There are two main approaches to GPS guidance systems. Tractor only steering and double steer systems.

Tractor only steering just uses the tractor's RTK (or equivalent) GPS high accuracy auto steering system to guide the hoe. With full autosteer now being common this is a simple way to automatically steer row hoes. However, there are limitations with this approach. First is that the autosteer is set up to get the tractor in the right location while the row hoe is located on the three point linkage, so, there can be some misalignment between the tractor location and where the row hoe needs to be. Also there are particular alignment issues when turning into a row whereby the hoe is not aligned until some distance up the row, requiring some forward-backward shuttling to achieve start of row alignment, which is time consuming.

GPS implement steering, called double steer for short, has a GPS antenna mounted on both the tractor and the implement with a means of steering the implement independently of the tractor, e.g., steering wheels or side shift on the three point linkage. Typically both tractor autosteer and implement steer are part of a single GPS system. Implement steering originated to assist contour cropping, to keep three point linkage equipment on the correct line and prevent it sliding / crabbing down the slope.

While full RTK GPS autosteer is really straight, double steer is even straighter and more accurate! In addition, where side shift, rather than ground steering systems (section 5.23.5), are used to steer the implement, it can position the hoe directly over the crop row while it is off the ground. This means the tractor can be turning into the crop row, but, not yet perfectly aligned on the crop rows, while the side-shift has moved the hoe exactly over the rows, so it can be lowered onto the crop rows even when the tractor is not in the correct position. This 'above-crop positioning' is a very significant advantage in time saving and accurate row starting, both for GPS and vision systems.

Because GPS systems work off A-B lines, **all** equipment involved in sowing / planting, row hoeing and other crop row work has to use full RTK GPS autosteer on exactly the same A-B lines, most likely, exactly the same GPS equipment, or they could be misaligned, especially at the high degree of accuracy required for row hoeing. Where double steer systems are used, the drill / planter should (must) be also used on the double steer system for the best results, particularly start of row placement.

An advantage of GPS is it is crop and weed agnostic - it does not even know the crop and weeds exist. Therefore it will weed any crop and any density of weeds.

RTK GPS accuracy is limited by signal correction, so the distance to base stations can be an issue. Longer distances to base station(s) may result the correction signals being too slow in reaching the tractor, such that accuracy drops to the point that crop damage occurs. Base stations may therefore be required close to the field to achieve sufficient accuracy or wider intrarow / crop gaps are needed reducing weeding efficacy (section 5.14.9).

5.23.3. Computer vision systems

As computer vision systems are guided by the actual crop rows in front of the hoe this avoids the requirement with GPS systems to use the same guidance system for drills / planters and the hoe. Clearly, row hoe vision systems cannot be used for planting / drilling as there are no crop rows to follow! While vision systems can successfully follow wavy rows, this will reduce overall accuracy and speed. In comparison, straight rows reduces the amount of sideways adjustment the hoe has to make, improving all aspects of its performance. Thus while a crop could be hand steered at drilling / planting and hoed with computer vision, with the multiple advantages of full tractor RTK autosteer, using it to ensure crop rows are drilled / planted as straight as possible, will maximise the efficiency, accuracy and speed of computer visions systems following RTK GPS planted rows. Vision systems, as they are being guided by the crop directly in front of the hoe are more accurate than GPS systems.

While there are many companies selling row hoes with vision guidance systems there are far fewer companies actually producing the vision systems, i.e., many weeder companies use the same underpinning vision hardware & software systems. Each vision system has pros and cons. For example some systems measure leaf surface area, which is good for transplanted vegetable crops with larger leaves, others identify the crop by shape determining the center of the crop plant. Some work only in two dimensions (2D) some use 3D (stereoscopic) / depth vision. Most use standard RBG (red, green, blue) cameras, others use multi-spectral / infrared. There are therefore different capabilities among the cameras and software interpreting the images and therefore performance of the overall vision systems in different crops.

Camera location is also an important factor to consider. Some cameras look straight down, others look ahead. On hoes wider than the tractor, look ahead cameras can be mounted on the outside of the hoe so they are looking at the crop alongside the tractor. On hoes narrower than the tractor, there needs to be sufficient forward view of the crop for the camera to see between the hoe and the back of the tractor.

It is therefore vital to check with the manufacturer / reseller that the vision system fits your row hoe configuration and is capable of accurately following the rows of your specific crops at all the growth stages they need to be weeded. Compared with GPS which is crop and weed agnostic, vision systems have to be able to differentiate the crop from the weeds, which can be a challenge in high weed populations and when the crop is bigger. Vision systems are however continually improving in this respect.

5.23.4. Crop sensor wands and ridge or furrow guidance

Prior to the advent of computer guidance systems, one form of automated guidance was based on crop sensing wands running along the crop stems (Figure 48). This required that the crop have a sufficiently large, prominent and stiff stem, like maize, for the wand to run against. The same principle is used on perennial crop weeders where the wands hit the crop trunk and support posts and then moves the weeder around them.

Figure 48. Automated guidance system using crop sensing wands.

A small, but increasing number of vision systems are being paired with crop sensing wands for crops with large upright stems that wands can run against. Thus when the crop is larger and has spread out so much it obscures the center of the crop rows from the cameras, the guidance system can use both camera and/or wands to best determine the crop row location.

There are also a range of other mechanical guidance systems, for example, that use a furrow put in at planting, or on ridges follow the ridge. Some of these are still sufficiently effective, and less expensive than computer guidance systems, that they are still completely viable guidance approaches.

5.23.5. Computer guidance steering system designs

Computer guidance systems need some means of steering / system to move the hoe independently of the tractor, and for GPS double steer systems also steering the drill / planter. A considerable number of approaches have been tried over the years, most have fallen by the wayside. They now mostly fall into one of three approaches in order of popularity:

- Hydraulic side-shift,
- Parallelogram side shift,
- Soil engaging steering wheels.

Hydraulic side shift uses hydraulic rams to move the implement side to side on some form of slider system (i.e., the three point linkage is not moving). A key advantage is they can be quite compact, in terms of their front to back width, which can be importance for minimising the distance between the row hoe and the back of the tractor (Figure 49). They are also often quite a simple design, e.g., using PTFE bushes though with the slider rods move, with, a double acting hydraulic ram.

Parallelogram side shifts use a heavy duty, side to side, parallelogram between the three point linkage toolbar and weeding unit toolbar moved by hydraulic ram (Figure 49). These are typically longer front to back than straight side shift systems due to the length of the parallelogram arms.

Steering wheels system have soil engaging wheels that pivot, just like the front steering wheels on a standard tractor, again controlled by a hydraulic ram, thus steering the hoe. Some swing on the three point link arms, others have separate means of allowing the hoe to move sideways, e.g., a slider system. These are less common and there may be a number of reasons for this. With steering wheels, the guidance system can only steer the hoe once the wheels are on the ground, so, they can't position the hoe over the crop rows while it is lifted up on the three point linkage as can side-shift and parallelogram units can, so, the more accurate start of row positioning of those systems is lost. Where the tractor link arms are used to allow sideways movement, the hoe or other equipment swings in an arc, which, changes the row spacings slightly. Particularly where the equipment swings towards the limit of sideways movement this may be enough to cause mismatch of the hoe gaps and the crop rows, or other problems, e.g., hoes or coulters not working correctly. In addition the response speed and precision of steering wheel systems is likely to be lower than for side-shift or parallelogram systems.

Figure 49. Computer guidance steering systems. Left, three photos hydraulic side shift. Right, parallelogram side shift.

One issue with guidance systems that push against the tractor, such as side shifts and parallelograms, is Newton's Third Law "For every action, there is an equal and opposite reaction" such that the force being exerted by the hydraulic rams to move the row hoe in one direction is exerting exactly the same force on the tractor in the opposite direction, which can push it off course. It is the tractor's heavier weight and larger friction against the soil that stops the sideways motion being equal for both. However, even on large tractors with small hoes, the sideways movement can still be a problem. To eliminate or minimise this effect ground wheels, e.g., pneumatic or steel, or disks, are used (Figure 49). Having disks or ribbed steel wheels that cuts several centimetres / inches into the soil is the preferred option as this most effectively minimises tractor movement. Ideally there should be no push against the tractor at all, all sideways forces are repulsed by the disks or wheels.

`Where hoes are wider than the planter / drill, or just where hoes are very wide, multiple independent steering systems are likely to be required. Even with GPS double steer systems there is still sufficient variation in distance between drill / planter bouts, that using a hoe to cover two or more bouts may result in crop loss unless the crop gap / intrarow space is made sufficiently large. Larger intrarows may not be an issue when crops are larger and weeding very close to the crops is no longer required, but it is often critical when crops are small.

5.23.6. Manual guidance / steering — tool carriers and manual steerage hoes

Before computer guidance systems were invented there were only manual guidance systems. While manual steering systems are slower, less accurate and have a much higher demand on the operator, their advantage is they have little or no capital cost on top of the weeder or tool carrier itself. There are also many second hand weeders and tool carriers available, including those pre-dating the herbicide era / 1950s, particularly in North America where they are still widely used by smaller organic farmers and growers. So, while computer guidance systems are game-changing there are still many reasons why manual steering may still be used.

There are four main approaches.

- Setting up a camera on the hoe linked to a screen in the tractor cab and manually steering.
- Having a steering system on the hoe that a second driver seated on the hoe steers (Figure 50).
- Front mounting the hoe on a standard tractor, either with front three point linkage or with a special adaptor (Figure 51).
- Specialised tool carrier tractors with mid-mounting (Figure 52).

The biggest challenge with all manual steering systems is operator metal fatigue. It requires a very high level of continual concentration and exceptional driving skill to keep the crop row passing through the gaps in the hoe or aligned with a marker. This is a much higher requirement than 'simply' steering a tractor straight in the right location, which itself requires a high level of concentration and skill. For some systems a significant amount of physical strength is required to steer the hoe, resulting in physical fatigue as well. Thus, depending on the level of precision required, an operator may only be able to work for an hour or so before their work performance drops and they need a break.

High resolution video cameras and tablet computers can be linked such that the camera is mounted on the hoe (the same location as for computer vision systems) and the tablet in the tractor cab, e.g., in front of the steering wheel, such that site lines on the tablet screen can be used to manually steer the tractor. With the comparatively low cost of cameras and tablets this can be a quick an inexpensive way of more accurately guiding the hoe than just steering the tractor, but, it still requires high levels of concentration.

The second driver system (Figure 50) is probably as old as three point linkage hoes themselves, going back to the days of horse drawn hoes. The challenge is still hoe operator fatigue — the tractor driving job is much easier — and that an extra person is required for the job, doubling labour costs.

Figure 50. Rear mounted interrow hoes with manual steering system and second operator.

Front mounting (Figures 51 & 53) was uncommon due to the need to have specialised / custom mounting systems, until front three point linkages themselves become common making front attachment much simpler and easier. Unless the hoe has been purpose designed to be front mounted, reconfiguration of a rear mounted hoe is required, from simple additions such as additional depth wheels, through to completely different toolbar designs. This is because the hoe is now being pushed rather than pulled, completely changing its physical dynamics.

For standard tractors where the bonnet obscures the view directly in front of the tractor, the tractor driver needs to lean sideways to be able to clearly see a crop row passing through the weeder. This can quickly become uncomfortable. Site guides can be setup in the center of the hoe, but, as these are looking some way ahead of the hoe position misalignment can still occur. As the driver can't see the area of the hoe in front of the tractor they also cannot see if there are blockages in the hoe or other problems without stopping the tractor to check. A video camera feed could solve this problem, and avoid the driver having to lean to the side to view the hoe, but at additional cost and complexity.

Figure 51. Front mounted interrow hoes. On front three point linkage (left), on dedicated mount (right).

With front mount systems, due to the steering wheels being behind the hoe, steering the hoe takes on some of the issues of rear-wheel steer vehicles like forklifts and combine harvesters, that steering motion is amplified. Plus the weight of the hoe and resistance to sideways movement can make steering quite different / difficult compared to without the hoe. With front mounted hoes on GPS autosteer tractors there can be an interaction between the hoe's movement and the tractor steering due to Newton's 3^{rd} Law (section 5.23.5) with the steering continually over or under compensating, thus requiring different software settings when driving with and without a hoe.

Where interrow hoeing is a common farm activity, tool carrier tractors with mid-mounted weeders are the preferred, if more expensive option (Figure 52). The same as a road-grader, mid-mounting between two axles give the most precise depth control - important for weeding rigs with manual rather than ground following depth control. It also has the most accurate steering, because opposite to a front mounted weeder, the movement of the steering wheels is de-amplified, allowing more precise guidance. Some tool carriers have offset driving positions so the driver can sit up straight and look directly ahead improving ergonomics. The most advanced tool carriers have the entire engine and drive-chain under or behind the cab / drivers seat, with one or two beams between the cab and the front wheels giving the driver the best possible view of the entire hoe (Figure 52).

Figure 52. A diverse range of tool carriers, old and new.

With all manually steered approaches, using a sight-guide, e.g., a brightly coloured vertical rod (Figure 53), to line the crop up against as the steering point of reference, is invariably superior to using the crop passing between weeding tools. The vertical rod is easier to see, can be placed in a more ergonomic position, and its height allows the driver to scan up and down its length, against a longer length of crop row than between two weeding tools, allowing a kind of average measure of the crop row location, especially if rows are not completely straight.

Figure 53. Crop guides on front mounted row hoe.

6. Alternative interrow hoe designs - a very brief guide

6.1. Key points

- While for many years the different interrow designs were mostly equals, modern, especially 2nd Generation row hoes are now the clear winners in the row-crop weeding race.
- Other designs, such as the rotary tiller, brush hoe, basket weeder and vertical axis rotary weeder are now niche machines.
- However, there are soil and weather situations where brush hoes and vertical axis weeder can achieve good weed management when row hoes are stuck in the shed.
- The basket weeder retains its niche due to low cost and mechanical simplicity.
- There is a small but growing range of simple designs of interrow hoes for arable crops.

While modern 'Swiss army knife' modular, parallelogram row hoes are able to weed in a very wide range of crops and conditions there are a small number of alternative interrow weeders, with some unique attributes, that means they may be a viable alterative or companion to a modern modular row hoe, mainly on high intensity market garden operations. These interrow hoes are more like a sheath knife, or a one trick pony.

6.2. Rotary tiller / cultivator

The interrow rotary tiller or cultivator is adapted from the tillage machine also called a rotovator and rotary hoe (both British English). It consists of a series of small, independent rotary tiller 'heads' that fit between the crop rows (Figure 54).

Figure 54. Interrow rotary tiller.

Due to the size of the heads these can only be used in wider crop rows, e.g., > 40 cm / 16". Their weeding action is exceptionally aggressive compared with other weeders including other powered weeders such as brush hoes and vertical axis powered weeders (see below). This means they can kill large weeds, work in difficult soil conditions, e.g., hard rubbly tilth, or hard packed, and cut and incorporate thick layers of residue. But it also means they have the largest negative impact on soil health, particularly structure / aggregation of any weeder. They are also mechanically complex with lots of moving parts and gearboxes, meaning higher purchase and maintenance costs and have slower work rates as the blades need to rotate sufficiently quicker than forward travel speed. While common and widely used, their negative impacts, particularly on soil health, cost and work rates, means alternatives should be preferred.

6.3. Horizontal axis brush hoe

The next alternative is the brush hoe (Figure 55).

Figure 55. Horizontal axis brush hoe.

This unique machine uses a powered, horizontal axis rotor with large, tough, round brushes (like a road sweeper), to brush the weeds out of the soil. This is an aggressive weeding action, with the top few centimetres / inch of soil and all the weeds in it, being pulverised. It can therefore completely kill weeds in wet, sticky, and /or stony soil conditions that would prevent other weeders from even operating. It is thus ideal for autumn and winter planted vegetable crops, such as garlic, in climates where soils are wet and cold over winter, and/or where soils are likely to be wet at the time of critical weeding operations. There are now multi-bed machines using computer guidance systems for larger operations. Their downside is there is only one manufacturer. They are slower as the PTO powered brushes have to rotate several times faster than forward speed. They are complex machines with multiple moving powered parts. As the crops have to pass under the rotor, typically in crop protection tunnels, this limits the height and also width of crops that can be weeded. In dry conditions, particularly on soils with any appreciable amounts of silt and clay, they create a large amount of airborne soil dust, which may require the driver of manually steered machines to wear eye and respiratory personal protective equipment (PPE), and/or cause other issue, e.g., crop contamination. Changing any aspect of the brushes, e.g., the crop gap / intrarow width, requires the whole brush rotor to be removed and each individual brush ring to moved / changed, which can take a considerable amount of time, so, they need to be set up for a specific row spacing and intrarow width and kept at that setting. Thus there may be a need to have two or more brush hoes, one with a narrow and the other(s) with wider intrarow width(s). But for all their limitations, in some situations they are the only weeder that can do the job.

It is also not obvious how to attach intrarow weeders to a brush hoe, such as mini-ridgers and finger weeders, which are an ideal companion. Figure 56 shows a brush hoe with a custom built secondary toolbar under the hoe driver's feet, with mini-ridgers on telescopes.

Figure 56. Customisation of a brush weeder with a second toolbar under the hoe drivers feet onto which mini-ridgers have been mounted on telescopes.

6.4. Basket weeder

The basket weeder was another invention of the Buddingh Weeder Co. It consists of two horizontal axles with cylindrical wire cages - the 'baskets' - spaced along them and a differential chain drive between the axles, which forces the baskets to turn at different speeds making them to cut / scuff through the soil (Figure 57).

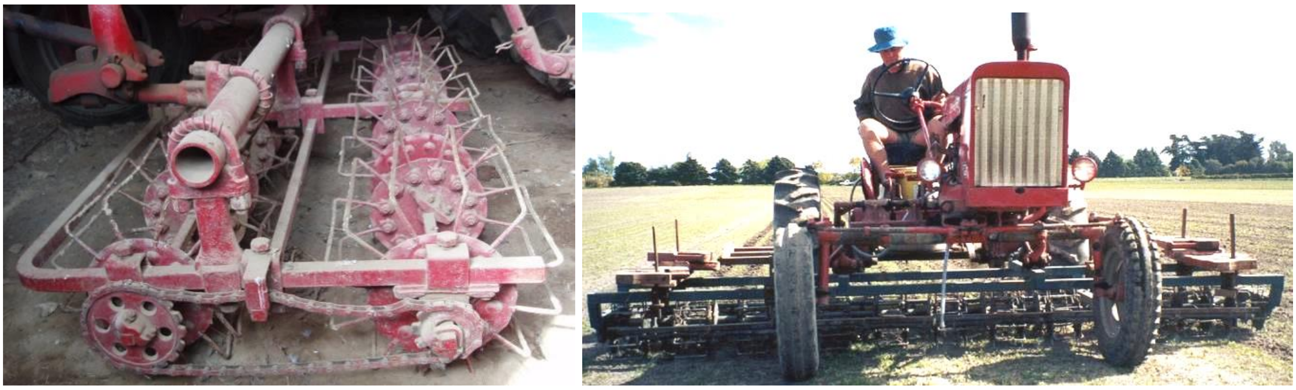

Figure 57. Original Buddingh basket weeder (left) custom built 10' weeder mid-mounted (right).

The advantages of the basket weeder is its mechanical simplicity and being ground driven, i.e., not requiring PTO drive. It is also the right size to replace the twin toolbars common on pre 1950s tool carriers (Figure 57), such as Farmalls and Allis Chalmers G, so it is popular with small scale organic market gardeners, particularly in N. America where the Buddingh Weeder Co. is based. They are sufficiently simple that many farmers have built their own machines, and, a very small number of European manufacturers also produce them. Their multiple limitations are such that they have never taken off for larger scale use. Issues include: The basket width is fixed so neither can the crop gap, requiring multiple machines with different crop gaps, though one European manufacturer has created width adjustable baskets, changing the width is still fiddly and time consuming. Basket weeders can only work in sufficiently soft soil tilths so that the basket rods can penetrate the soil. If the soil is too hard and/or too stony the rods can bend. It will only kill small weeds, e.g., up to two true leaves due to the less aggressive weeding action, and needs dry soil and desiccating weather conditions to work effectively.

As most basket weeders are mounted on old tool carriers, intrarow weeders, e.g., finger weeders, can be mounted on the rear three point linkage, if the tool carrier has one. Some custom built basket weeders are designed with a toolbar front and /or back of the axles onto which mini-ridgers and other small weeding tools and/or soil breaking tines, can be mounted (Figure 57).

6.5. Vertical axis rotary tine weeder

The vertical axis rotary tine weeder has a set of rigid metal tines (typically 3) on a vertical axis rotor (Figure 58).

Figure 58. Vertical axis rotary tine weeder.

The rotating tines are powered from the PTO, through a drive shaft and gear boxes. The advantages of the vertical axis rotary tine weeder is it is very aggressive as the rotating, rigid metal tines will cut through very hard ground and uproot large weeds, e.g., > 10 cm 4” high. There are thus situations where they may be the only weeder that will work. The downsides are similar to rotary tillers, brush and basket weeders. They are one-trick ponies, the weeding tools can’t be changed. Forward speed is limited as the tines have to have sufficient time to cut through all the soil while they are moving forward. Adjusting the crop gaps is time consuming, so, multiple machines may be required set at specific intrarow spacings. The number of crop rows is fixed, without adding or removing rotors, which is a substantial amount of work. They are mechanically complex, with multiple drive shafts and a gearbox for each rotor. They can throw soil some distance, which can contaminate crops, and create dust in dry conditions. While they can work in stony conditions, there is the potential for stones to lodge between the tines and/or get thrown from the machine at speed.

6.6. Simple interrow hoes for arable crops

There are also a small number of new interrow hoe designs going in the opposite direction to the complexity of parallelogram systems (Figure 59).

Figure 59. Simple / non-parallelogram interrow hoes for cereal crops. Left photo Claydon Terrablade claydondrill.com. right photo Sickle Hoe Leibing Maschinenbau dieter-leibing.de.

These are for robust crops such as cereal in standard rows, e.g., 15 cm / 6”. They have a single toolbar, from which an A blade or ducksfoot point (section 5.15) are mounted on the end of on a long sprung arm. They only weed the interrow and as the A or duckfoot blades move soil sideways the crop needs to be large enough to avoid burial. Typically these are front mounted so they are steered by the tractor. The toolbars width is limited to around 12 meters / yards as the weeder arms are only able to compensate for variations in ground height through the arm moving up and down which changes the weeding tool angle. As there is one arm and weeding tool per interrow, the only way to change the width of the weeded area is to change the weeding tool. What they lack in sophistication they compensate for in simplicity and thus lower cost.

7. Conclusions

Interrow hoes have come a very long way from Jethro Tull's initial idea! While there have been a diverse range of interrow hoe designs developed over the last decades, the modular, parallelogram row hoe, with its ability to mount a diverse range of both interrow and intrarow weeding tools, is now the clear winner. The degree of sophistication of 2nd Generation row hoes, with features such as automatic intrarow width adjustment and section control, is quite astonishing for machines that until recently were considered relics of a bygone era. Computer guidance systems, particularly camera based vision systems, are now a mature, highly effective and reliable technology. Particularly when coupled with RTK GSP tractor autosteer, the person in the tractor seat is no longer a driver, they have been relived of the mentally, and sometimes physically, gruelling tasks of steering, to become a machinery supervisor, to ensure that what are now complex machines are operating at peak effectiveness. With row hoe widths now reaching 30 meters / yards and forward speeds only limited by tractor and weeder, not human driver's reaction time, work rates and weeding control equivalent to herbicides are now possible. Thus, with the ever growing challenges facing herbicides, modern row hoes are now a key technology for Integrated Weed Management in row-crops and will play an even more important role in the future.

Happy weeding™

8. Further information and resources

There is limited scientific research and publications on mechanical weeding, and unfortunately much of it is of next to no use to farmers and growers, or scientists (Rasmussen, 2024). By far the best and most accessible source of information is online videos, for example, on YouTube! Seeing machines in action is worth a thousand words and a hundred photos. Search using terms such as 'mechanical weeding' 'interrow hoe' 'row-crop cultivator' etc. Many farmers and growers are putting up extensive videos, explaining what they are doing, and comparing and contrasting different types of row hoes, weeding tools and more. Weeder manufacturers' promotional and educational videos also abound, and are often helpful in understanding the basics of machine design and use, once beyond the sales pitch. AI generated subtitles with instant translation, means that language is much less of a barrier, even if the AI translators struggle with agricultural terms. There are even useful videos by agricultural research and extension organisations, including the excellent MSU Mechanical Weed Control channel youtube.com/@msumechanicalweedcontrol3534, which, among many others, are worth their weight in journal papers.

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