Contiguous (broadacre) Weeders.
Spring Tine Weeders, Rotary Tine Weeder, and Rotary Hoe.
A Comprehensive Guide.

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

About the author

Dr Charles 'Merf' Merfield MSRNZ is a world leading expert in physical weeding with over 35 years experience, including practical on-farm use, machinery design and construction, plus research. He has worked with nearly every kind of mechanical weeder in vegetable and arable cropping systems. He started in the late 1980s with a brush hoe at www.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 www.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 www.merfield.com/physicalweeding/flameweeding/ and inventing the direct-fired steam weeder www.merfield.com/physicalweeding/steamweeding/. 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 mechanical weeders, culminating in designing from first principles, as well as building, a high clearance row-hoe for sweetcorn. His time at Harts Creek Farm also involved using some of the first RTK GPS autosteer in New Zealand in the early 2000s which was game changing for interrow-hoeing, as well as using the first computer vision system in NZ which was more of a challenge. He has also optimised the design of the rigid tool clamp www.merfield.com/physicalweeding/merfclamp/ and his pride and joy is the 4 Wheel Hoe www.merfield.com/physicalweeding/fourwheelhoe/ a pedestrian row-hoe for small scale market gardens. He also provides one-to-one consulting, advice to farmers and growers, undertakes research, and presents at workshops and fieldays for industry, on all aspects of non-chemical and integrated weed management, as well as on soil health, biological pest and pathogen management and agroecology in general.

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Table of contents

1. Introduction **9**
- 1.1. Key points 9
- 1.2. Who this report is for? 9
- 1.3. The changing face of weed management - herbicide resistance and Integrated Weed Management (IWM) 10
- 1.4. The art of mechanical weed management 10
  - 1.4.1. The challenge for mechanical weeding research 10
- 1.5. Mechanical weeding is the finale — not the start of non-chemical and integrated weed management 11
- 1.6. The debt to Organic Farming 11

2. Overview of contiguous weeders **12**
- 2.1. Key points 12
- 2.2. The three types of contiguous weeders 14
  - 2.2.1. Overview: Vertical vs. horizontal weeding modes of actions (MoA) 14
- 2.3. How weeders kill weeds 15
- 2.4. Weed size is everything when it comes to timing weeding 15
- 2.5. Weed and crop plant growth stage terminology 16
- 2.6. Contiguous weeders will not kill established weeds but can help manage them 17
- 2.7. Immediate vs. longer term weed management 17
- 2.8. Contiguous weeders are crop row agnostic 17
  - 2.8.1. Matching drill and weeder bout widths 17
- 2.9. Killing the weeds not the crop — selectivity, tolerance, resistance and recovery in post-emergence weeding 18
  - 2.9.1. Crop soil cover (CSC) 19
  - 2.9.2. Using crop soil cover in practice 20
  - 2.9.3. The relevance of soil cover (CSC) for newly emerged crops 21
  - 2.9.4. Only use crop soil cover (CSC) measurements with tine weeders 21
  - 2.9.5. Selectivity - the importance of crop seed depth vs. weed seed depth 21
  - 2.9.6. Conclusions on killing the weeds not the crop 21
- 2.10. Increased sowing rates 22
- 2.11. Increased sowing depth 22
- 2.12. Trial and error - learning by doing 22
- 2.13. Weeding across crop rows 23
- 2.14. Soil and weather conditions 23
  - 2.14.1. Weather 24
  - 2.14.2. Soil moisture 24
  - 2.14.3. Soil tilth 24
  - 2.14.4. Stones and clods 24
  - 2.14.5. Residue 24
- 2.15. Contrasting and thus complimentary weather windows for herbicides and mechanical weeding 24
- 2.16. If at first you don't succeed, try, try again! 25
- 2.17. Don't over-weed at later crop growth stages 25
- 2.18. False seedbeds 26
- 2.19. Pre-crop emergence weeding (blind weeding) 26
- 2.20. Pneumatic seeders 27
- 2.21. Fertiliser application and incorporation 27

2.22. Visibility of working area 28
2.23. Variable widths on folding weeders 28
2.24. Arable vs. row crop vs. vegetable cropping systems — contiguous vs. incontiguous 28
2.24.1. Which contiguous weeder to start with for arable, row crops and vegetables 29
2.25. Integration with herbicides 30
2.26. Soil health impacts 31
2.27. Energy use 32

3. Spring tine weeders 33
3.1. Key points 33
3.2. Spring tine weeder design 34
3.3. History and origins 34
3.4. Target weed and crop plant sizes 36
3.5. How it works (mode of action) and how to use one 37
3.6. Tine angle 38
3.6.1. Going backwards 38
3.6.2. Tine bend angle 38
3.7. Downpressure 40
3.8. Forward speed 41
3.8.1. Putting it together - combining tine angle, downpressure and speed 42
3.8.1.1. An example of weeding a delicate crop in challenging conditions 43
3.9. Working conditions 44
3.9.1. Soil 44
3.9.2. Stones and clods 45
3.9.3. Residue 45
3.9.4. Weather 45
3.10. Tine horizontal spacing 46
3.11. Tine tip wear and carbide tips 46
3.12. Ridge weeding 46
3.13. Crop plant clearance 46
3.14. Raking out weeds 47
3.15. Big weeders - weight and wheels and working on slopes 47
3.16. Turing a contiguous spring tine weeder into an incontiguous weeder 48
3.17. Tine 'hooking' 49
3.18. Three 'generations' of spring tine weeders 49
3.18.1. 1St generation spring tine weeders 49
3.18.1.1. Adjustments 51
3.18.1.2. Tine attachment 51
3.18.2. 2nd generation spring tine weeders 51
3.18.2.1. Independent downpressure mechanisms 52
3.18.2.2. Pros and cons of 2nd generation spring tine weeders 53
3.18.2.3. Controlling tine angles 53
3.18.2.4. Tine sideways flex 54
3.18.2.5. Incontiguous operation 54
3.18.3. 3rd generation spring tine weeders 55

4. Rotary tine weeder 57
4.1. Key points 57
4.2. Rotary tine weeder design 57
4.3. History and origins 57
4.4. Target weed and crop plant sizes 59

4.5. How it works (mode of action) and how to use one 59
4.5.1. Forward speed 61
4.5.2. Downpressure 61
4.5.3. Wheel angle 62
4.5.4. Speed, downpressure and wheel angle interactions 62
4.6. Incontiguous weeding 62
4.7. Ridge weeding 63
4.8. Side thrust, weeding gap and extra weeding wheels 63
4.9. Working conditions 63
4.9.1. Soil 63
4.9.2. Weather 64
4.9.3. Residues 64
4.9.4. Stones and clods 64
4.10. Crop plant clearance 64
4.11. Perennial herbaceous crop spring cleanup 65

5. Rotary hoe 66
5.1. Key points 66
5.2. Rotary hoe design 66
5.3. History and origins 67
5.4. Target weed and crop plant sizes 69
5.5. How it works (mode of action) and how to use one 70
5.5.1. Why the rotary hoe's action is completely different to tine weeders: vertical vs. horizontal weeding action 70
5.5.2. Narrowing the wheel gap 72
5.5.3. Angled rotary hoe wheel designs 72
5.5.4. Rear spring tines 73
5.5.5. Reverse wheel designs 73
5.6. Working conditions 74
5.6.1. Soil including crusts 74
5.6.2. Weather 74
5.6.3. Residue 75
5.6.4. Stones 75
5.7. Replacing worn spoons 76
5.8. Crop plant clearance 76
5.8.1. Incontiguous weeding including ridge weeding 76
5.9. Summary of using a rotary hoe 77

6. Putting it all together 79
6.1. Arable / row crops 79
6.2. Vegetables 80

7. Conclusions 80

8. Further information 81

9. References 82

List of figures

Figure 1. Crop yield loss based on the amount of crop soil cover (CSC) for oats, barley, wheat triticale grown over two years. Based on (Rasmussen *et al.*, 2009). 20
Figure 2. Weed control: relative energy requirements, note log scale on Y / value axis. From (Bloomer, 2023). 32
Figure 3. Hatzenbichler spring tine harrow modular weeding frame. 34
Figure 4. Left: "Jointed harrow for weed control, made by R. Sack, Leipzig. Photograph by Sack." Right: "Sack's weed harrow, wide pattern, drawn by a tractor. The great length of the tines and the adaptability of the harrow to surface inequalities are seen. Photograph by Sack." From (Rademacher, 1940. p. 88). 34
Figure 5. The Ferguson weeder. Image credit www.fergusonclub.com/weeder. 35
Figure 6. "Das Original Hatzenbichler Comb harrow". Photo credit Hatzenbichler Agro-Technik www.hatzenbichler.com. 35
Figure 7. A range of spring tine weeders. Photo credits: bottom left, Chris Smith; bottom right, Treffler www.treffler.net. 36
Figure 8. Spring tine weeder mode of action. Nearly vertical tine (black line) rakes through the soil surface shallower than the crop seed depth (wheat) but deeper than weedling depth (No. 1). The tine impacts crop shoot bending it and partly covering it with soil (No. 2). The tine digs up and buries weeds by throwing soil in front and to the sides of the tine. (No.3). N.B. compared to the rotary hoe where the spoon is stationary relative to the crop (Figure 31) for tine weeders the tine is moving relative to the crop. 37
Figure 9. A range of spring tine angles from ~160° (left), the most common ~135° (middle) to now uncommon ~90° (right). 38
Figure 10. Five tine angles on a 1st generation Einböck spring tine weeder (modified for research plot use) from lowest angle top left to highest angle at the bottom left. 39
Figure 11. Effect of tine tip bend angle of 90°, 135° and 160° on the position of the tine leg at three tine-soil entry angles of 45° forward, 90° (vertical) and 45° backwards. 40
Figure 12. Digital hand / suitcase scales. 41
Figure 13. The amount of soil disturbance at 4 kph vs. 8 kph / 2.5 mph vs. 5 mph. Image credit Einböck www.youtube.com/shorts/dBVglrYwgos. 42
Figure 14. The edge of a carrot seed crop, using manually transplanted steckling, that have been weeded with a spring tine weeder, showing the difference in weed populations with the tilled / cultivated but unweeded ground on the left and weeded crop area on the right. The plough furrow is visible in top left of photo. 44
Figure 15. Example of a 'hooked' tine. 49
Figure 16. Einböck spring tine weeder, modular wishbone and frame (left) larger weeder folded for transport (right). Pneumatic seeder distribution pipes and seed outlets can be seen on the left hand photo. 50
Figure 17. Rear depth wheels on a 1st generation Einböck AEROSTAR-EXACT spring tine weeder. Photo credit www.einboeck.at 51
Figure 18. Treffler coil spring and wire rope downpressure system. 52
Figure 19. Independent downpressure mechanisms on 2nd generation spring tine weeders. Coil spring with hydraulic adjustment (left, photo credit Chris Smith), pneumatic (center, photo credit Chris Smith), direct hydraulic (right). Right photo shows single frame design, center photo shows original modular wishbone design. 52

Figure 20. Effect of frame height (red rectangle) on tine-soil angle, based on a tine tip bend angle of 110°. 54
Figure 21. Computer vision system for continuously adjusting spring tine weeding intensity. Image (Spaeth *et al.*, 2021). 55
Figure 22. Various rotary tine weeders. Einböck (top left) photo credit www.einboeck.at, APV (top right) photo credit www.apv.at, ANNABURGER (bottom left) photo credit www.annaburger.de, Feelcrop (bottom right) photo credit www.feelcrop.com. 58
Figure 23. A range of intrarow vertical moving wire weeders. Left photo credit Steketee. 58
Figure 24. Rotary tine weeder mode of action. The spoked wheels are angled at around 30° to the direction of travel such that they rotate more slowly than forward speed. Consequently the spokes rake through the soil surface as they turn while at the same time being pulled through the soil (No. 1). Tine depth must be shallower than crop seeding depth (No. 1). The rotating tines initially tend to push the crop foliage sideways and downwards as they descend towards the soil surface, while starting to comb out the weeds and rake up residue (No. 2). Then as the tines lift up and away from the soil surface they tend to lift the crops' foliage back up again, ripping it off at higher speeds, while also finishing combing weeds out of the soil (No. 3). 60
Figure 25. Extra set of weeding wheels to weed the gap between the two main sets of left and right facing wheels. Set in front (left) photo credit www.feelcrop.com, and behind (right) photo credit www.einboeck.at. 63
Figure 26. Rotary hoes. John Deere (left), Case IH (right) photo credit www.tractorhouse.com. 67
Figure 27. US Patent No. 510,812 (1893) inventors William L. Nieman and William Hieronymus, for a 'cultivator' i.e., rotary hoe. Image credit www.rotary-hoe.com/wp-content/uploads/US-Patent-510812-für-die-erste-Rotary-Hoe-Version-vom-Dezember-1893.pdf, www.rotary-hoe.com/geschichte/. 67
Figure 28. Early 1900s horse drawn rotary hoes. Moline rotary hoe from 'Moline Flying Dutchman Farm Implements. General Catalogue No. 60. Moline Implement Company, Moline Illinois.' (top row, and bottom left) image credit www.smallfarmersjournal.com/rotary-hoes-vs-cultimulchers, Massey Ferguson USA early tractor mounted rotary hoe (bottom right) photo credit www.schneiderauctioneers.com. 68
Figure 29. KUHN Starliner using a traditional design (left) photo credit www.profi.de, Einböck ROTARYSTAR with novel section based, hydraulic, parallelogram depth / downpressure control system (right) photo credit www.einboeck.at. 69
Figure 30. Traditional rotary hoe wheel (left) spoon shaped spoke tips (center and right). 70
Figure 31. Rotary hoe mode of action. The angled tip / spoon enters the soil vertically (No. 1) then as the weeder moves forward the wheel rotates such that the spoon is stationary in the soil, i.e., it has no horizontal motion through the soil, so is stationary relative to the germinating maize / corn seedling and small weedling. As the wheel rotates to the point that the spoke is vertical, the spoon is now pointing backwards (No. 2) and still positioned above the maize seedling. Then as the wheel continues to rotate the spoon exits the soil nearly horizontally so that it flings the soil and weedling on the spoon into the air while leaving the deeper maize seedling unharmed (No. 3). Note: that the spoon is stationary in relation to the soil and crop is the opposite of spring and rotary tine weeders where the tines are moving relative to the crop (Figure 8). 71
Figure 32. Double toolbar Yetter rotary hoe. Photo credit www.bidnow.us. 72

Figure 33. Rear spring tines on a rotary hoe. Left image credit www.rotek-technik.de, right image credit https://ien.kverneland.com. 73
Figure 34. High residue rotary hoe with much larger spacing between the two banks of wheels to minimise clogging. 75
Figure 35. Effect of stones on spoon tips. 75
Figure 36. Worn (left) and new (right) traditional rotary hoe wheels. 76

1. Introduction

This report is a guide to contiguous (broadacre) weeders as a whole, the three main types, their origins, mode of action, and how to use them. This is one of a pair of reports on mechanical weeding with the updated BHU Future Farming Centre report "Modern (inter)row-hoes. The Swiss army knife of mechanical weeders. A comprehensive guide V1.1." (Merfield, 2026a) www.bhu.org.nz/future-farming-centre/information/bulletin/the-ffc-bulletin-2026-v4-mechanical-weeding-for-annual-crops-a-comprehensive-guide/. Together the two reports provide a comprehensive guide to modern mechanical weeding focused on annual cropping systems (arable, row crops and vegetables) and their place within Integrated Weed Management (IWM).

1.1. Key points

- This report is for annual cropping farmers and growers wanting or needing to use mechanical weeding, as well as scientists, extension and those supporting producers.
- Weed management is changing increasingly rapidly due to herbicide resistance, very little new herbicide chemistry, increasing regulation and consumer concerns.
- Integrated Weed Management (IWM) is the only way forward for weed management and mechanical weeding is the key direct alternative for herbicides in cropping within IWM.
- Mechanical weeding is as much an art as a science and requires practical experience to use it most effectively. This is a challenge for research as the experimental approach used for herbicide research is mostly unsuitable.
- Mechanical weeding in cropping systems is the icing, even the cherry on the cake, most weed management must be achieved before a crop goes in the ground.
- It is entirely thanks to organic farming that modern mechanical weeding exists, and were this not the case mainstream farming would now be trying to face the challenge of herbicide resistance with far fewer options.

1.2. Who this report is for?

This report is aimed at mainstream commercial farmers and growers of annual crops, i.e., arable / row crops and vegetables, who want, or have to, reduce or even eliminate the use of herbicides, through mechanical weeding. As the primary use of contiguous weeders is in arable / row crops (e.g., wheat, maize / corn, oil seeds, beans, etc.) these are the context for the report. Vegetable crops are included but at a secondary level as the incontiguous row-hoe is the primary mechanical weeding tool for these systems (section 2.24).

For those new to mechanical weeding, and even older hands, the range of different types of machines can be daunting and confusing. This report, and its updated sibling report "Modern (inter)row-hoes — The Swiss army knife of mechanical weeders. A comprehensive guide V1.1." (Merfield, 2026a) provide the detailed information required to understand modern mechanical weeding, what machines to use and how to use them in different cropping systems.

This report is also for organic producers and anyone who is already using mechanical weeding and want to improve their knowledge of contiguous weeders.

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 and undertaking, and also undertaking mechanical weeding research.

In all cases it assumes a good understanding of annual crop farming and growing systems, including of machinery used in these systems, particularly, tillage / cultivation machinery.

1.3. The changing face of weed management - herbicide resistance and Integrated Weed Management (IWM)

A key driver in the wider resurgence of mechanical weeding is that herbicides are facing ever increasing challenges — principally herbicide resistance coupled with very limited new chemistry, plus legislative and consumer 'resistance', such that herbicide based weed management is starting to fail against some key weeds in staple crops. Coupled with herbicide resistance, is the ongoing expansion of organic agriculture and agroecology, which prohibit, or aim to minimise, the use of synthetic herbicides (and pesticides as a whole).

In response to both these issues, weed scientists have developed the concept of Integrated Weed Management (IWM), that integrates as many different weed management tactics as possible (Riemens *et al.*, 2022; Merfield, 2023a). Within IWM, mechanical weeding is a key component, and the primary direct replacement for herbicides in annual crops. Once the preserve of organic producers, mechanical weeding is now such an important technology, that in the last decade it has become mainstream.

1.4. The art of mechanical weed management

Mechanical weed management, particularly with contiguous weeders, is as much an art as a science. As Gunsolus (1990) states:

"It is apparent that nonchemical weed control is as much an art as a science. Science can help us explain why certain practices work the way they do and can define basic principles that can be used in predicting the outcome. However, weed control practices such as rotary hoeing and cultivation also require knowledge of how to accomplish a given task (e.g., adjusting equipment) on a given soil type under given soil conditions. This is the art of weed control.

Well-conducted science can contribute substantially to a farmer's knowledge. However, science can only assist, but not substitute for, the highly refined management skills that are necessary to develop and carry out a successful non-chemical weed control program." (Gunsolus, 1990).

Herbicide based weed management is akin to 'painting-by-numbers': based on crop and weed species, herbicide chemistry and application methods can be looked up in pre-determined tables, and implemented with little need for further knowledge or skill. Indeed, part of the reasons for the rapid uptake of herbicides (and pesticides as a whole) is they dramatically simplified, and were considerably more reliable, than the non-chemical weed management techniques that predated them. With the post-herbicide era (Marshall, 2019) now well underway, and with mechanical weeding being the dominant direct herbicide replacement, weed management is returning from the recipe approach of herbicides to the art of mechanical weed management. This means, as per Gunsolus, that farmers and growers need to develop "the highly refined management skills that are necessary to develop and carry out a successful non-chemical weed control program". As discussed in section 2.10, developing those skills is done though trial and error, as well as watching the trials and tribulations of other farmers in online videos (see section 8) and resources such as this report.

1.4.1. The challenge for mechanical weeding research

This also highlights the challenge for weed scientists, particularly herbicide scientists, researching mechanical weeding. That it is an art as much as a science means that the skill and knowledge of the machinery operator can have a big impact on the results, even bigger than treatment effects. Too many mechanical weed management experiments use herbicide thinking and trial designs that will fail to achieve the full weed control potential of mechanical weeding. Too many experiments just replicate on-farm use without any theoretical underpinning (Rasmussen, 2024). The best proof of the effectiveness of mechanical weeding lies not in experiments, but farmers and growers with years of experience and expertise that are achieving herbicide levels of weed management across tens of

thousands of hectares / acres, year-on-year, using only mechanical weeding. Mechanical weeding works: more research attempting to show if mechanical weeding works adds no value or new knowledge. Where science can help, is as Gunsolus states, developing a deeper understanding of the mechanisms by which weeders work, improving designs, understanding crop impacts and therefore better understand how to optimally use mechanical weeders. As Rasmussen (2024) says "Stop wasting time on mechanical weed control research that lacks a theoretical foundation".

1.5. Mechanical weeding is the finale — not the start of non-chemical and integrated weed management

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, 2023a). In these systems, mechanical weeding is the icing on the cake, even the cherry on the cake. So while modern mechanical weeders can achieve very high levels of in-crop weed management, they are not enough by themselves. The metaphor of "many little hammers" (Liebman & Gallandt, 1997) speaks to the need to have diversified weed management tactics in non-herbicide weed management systems in contrast with the sledge hammer of herbicides. The many little hammers metaphor applies both to the whole farm system, e.g., the use of rotations and integration of cropping with pasture based livestock, as well as mechanical weeding itself. It speaks to the fact that most mechanical weeding passes wont achieve 100% weed control compared to the often near 100% control of individual herbicide applications. Mechanical weeding thus needs to use a stacked sequence of techniques, e.g., initial tillage / cultivation such as ploughing (inversion tillage), then false seedbeds, stale seedbeds, pre-em weeding and then several post-emergence weeding passes with different tools. Each is a 'little hammer blow' against the weeds that adds up to a 'sledge hammer blow' overall. So key to effective mechanical weeding is ensuring that there sufficient hammer blows, i.e., weed management operations, such that they cumulatively achieve good overall weed management. Many little hammers also builds resilience into weed management, if any one tool fails to achieve the required level of weed control, other tools can pick up the slack. This again compares to herbicides, where a failure, e.g., it is too dry and a residual fails, can be harder to recover from.

So if more than 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!**

1.6. The debt to Organic Farming

It needs acknowledging that the existence of modern weeding machinery is almost entirely due to organic farming, 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. Without organics, mainstream agriculture and horticulture would find themselves in the position of having very limited direct alternatives to herbicides. It would be impossible to compress the last 80 or so years of mechanical weeding practical experience, innovation, research and development, into the kind of time-spans that would be required if modern mechanical weeding did not exist, and needed to be developed in haste. It 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 mainstream farming's disposal, and therefore the size of the debt owed to organic agriculture.

2. Overview of contiguous weeders

This chapter gives a brief introduction to the three types of contiguous weeders and a range of attributes and issues that all contiguous weeders share.

Contiguous and incontiguous weeders are terms I have coined for want of better names to describe and differentiate weeder types. Contiguous weeders are also called a range of other names including, broadacre, broadcast, row-independent and blind weeders (the term 'blind' is used in multiple and even contradictory ways in mechanical weeding so being clear how the term is being used is vital). Contiguous weeders are so-called as they weed the entire field surface with a uniform weeding action, applied to crop and weeds alike, so the weeding tools are contiguous across their entire width. This contrast with incontiguous weeders that have different weeding tools with different weeding actions, for the interrow and intrarow (crop row), so the weeding tools are incontiguous across the width of the machine.

2.1. Key points

- Contiguous weeders are so-called as they weed the entire crop surface, crop and weeds alike so their weeding tools are contiguous across the weeders width.
- There are three main types of contiguous weeder: spring tine weeder, rotary tine weeder and rotary hoe. The tine weeders have a horizontal raking action while the rotary hoe has a vertical lifting action such that they have very different impacts on crop and weeds.
- All mechanical weeders kill weeds through three actions: uprooting, severing and burial. Weeders vary in the proportion of weeds they kill through the three actions which can have a significant impact on their efficacy in different crop, weed, soil and weather conditions.
- Mechanical weeding must always target cotyledon stage weeds. Using the typical herbicide approach of weeding by crop growth stage will fail, potentially catastrophically.
- Contiguous weeders are only effective against small weeds, i.e., cotyledon to a few true leaves maximum, and will not kill established weeds. But they can help manage them.
- Integrated Weed Management (IWM) takes a longer term and system view of weed management with minimising weed seed rain in annual crops a key foundation. Effectively controlling weeds around crop establishment is one of the key means of minimising weed seed rain.
- Contiguous weeders are crop row agnostic, i.e., it does not matter where the rows are, their spacing, widths etc., contiguous weeders can weed any row configuration including broadcast crops.
- While contiguous weeders can be driven any direction across a field, best practice is to use the drill wheel tracks for weeding and therefore correctly matching the weeder width to the drill width is essential.
- As contiguous weeders weed crop and weed alike the crop needs to survive the weeding action that kills the weeds. The concepts of: selectivity, tolerance, resistance and recovery were developed in mechanical weeding research to create a framework to understand crop survival and weed kill.
- Crop soil cover (CSC) was created as a standardised measure in spring tine weeder research, mostly in cereals, being the amount of crop foliage covered by soil after weeding. It is an important concept to understand and can be used in the field when tine weeding to check that crops are not being excessively harmed. It is not considered valid for rotary hoeing due to the different mode of action.
- A key reason contiguous weeders kill weeds but not the crop is that the crop has larger seeds and is sown deeper than the depth where most weeds emerge from.
- Increasing sowing rates as well as sowing deeper are valuable establishment techniques to maximise contiguous weeding efficacy while maintaining yield.

- As mechanical weeding is as much an art as a science, and as the number of mechanical weeding scientific experiments are very limited, undertaking on farm trials, i.e., learning by doing, is essential for learning the art of mechanical weeding and also working out how best to use each weeder in different crop and weed scenarios.
- Mechanical weeding is often thought to only be viable in hot, dry soil and weather conditions. This is incorrect, and it can maintain efficacy even in cool moist conditions. It is however still important to understand how the weather and soil conditions (including stones and residue) impact on weeder performance and what their limitations are.
- Herbicides and mechanical weeding have contrasting and thus complimentary weather windows which mean when both techniques can be used the weeding weather window is much larger.
- Results from multiple experiments that test the impact of weeding on yield indicate that using contiguous weeders as the crop gets bigger can significantly reduce yield, so should be avoided.
- False seedbeds are where the soil is tilled ready for planting but then left for a weed flush to emerge. That is then killed with the least amount of soil disturbance possible. False seedbed's are a vital part of annual crop weed management that was widely used before the herbicide era.
- Likewise, pre-crop emergence weeding (often called blind weeding) is a key weed management technique in widespread use before herbicides and should be used as often as possible with mechanical weeding.
- Arable, row crop and vegetable cropping systems need different types of weeders and different orders in which they should be purchased. Due to the difference among weeders having all of them will maximise the ability to achieve good weed management.
    - Arable systems should start with a spring tine weeder, then add a rotary hoe where soil capping is a common issue otherwise a rotary tine weeder is a better bet due to a wider range of crop and weed growth stages it can be used in.
    - Row-crop systems typically start with a rotary hoe due to historical president, and the ability to break soil caps / crusts plus weeding around emergence with minimal crop damage. Once the crop has established, a spring tine weeder would give better weed control. However, a rotary tine weeder could stand in for both, though with a risk of crop damage around emergence if not used very carefully. Due to the wide row spacings an (inter)row-hoe (cultivator) is an essential part of the mix.
    - Vegetable systems should start with the incontiguous row-hoe utilising a range of intrarow weeders, and only then consider a spring tine weeder or possibly rotary tine weeder. The rotary hoe is considered unsuitable for most vegetable crops, principally due to soil throw.
- There are huge benefits integrating mechanical weeding with herbicides to play to the strengths of each, while reducing the risk of herbicide resistance.
    - Band spraying (particularly pre-emergence residual herbicides) and interrow hoeing is the most common and obvious form of integration.
    - Contiguous weeders can be used as a direct substitute for a broadcast herbicide application, particularly post-emergence.
    - Integrating residual herbicides with mechanical weeding is where interactions (i.e., more than just integration) occur, potentially both boosting and destroying herbicide efficacy depending if the herbicide is root or shoot absorbed and needs incorporation or to form a skin / cap. There is very limited research on this, so on-farm trials are essential.
- Concerns are often raised about the soil health impacts of mechanical weeding. Most of these are unsupported by science. However, many of the claims of benefits to soil health from mechanical weeding replacing herbicides, especially by weeder manufactures, are equally unsupported by science.

- Likewise energy use is often raised as a problem for mechanical weeding, however, when the embodied energy in herbicides is taken into account mechanical weeding can have an order of magnitude lower energy consumption.

2.2. The three types of contiguous weeders

While a range of contiguous weeders have been developed over the decades, many have been found wanting and have fallen by the wayside, leaving three types of contiguous weeder that are now in widespread use. They are defined in this report as the:

- **Spring tine weeder**, also called tine harrows, spring tine harrows, tine weeder, finger harrows, flex-tine harrows / weeders, weed harrows, comb harrows, finger weeders (the name finger weeder is now mainly used for an intrarow weeder on row-hoes see (Merfield, 2026a)) and combinations of the above.
- **Rotary tine weeder**, also called rotary tine harrow, rotary harrow, rotative weeder, and *UniHacke*, *rollhacke* and *rollstriegel* in German.
- **Rotary hoe**, occasionally called a spoon weeder, and *rollhacke* and *rollstriegel* in German.

In this report, where both spring and rotary tine weeders are being referred to together the term 'tine weeders' is used. Where an individual tine weeder type is being referred to the full name is used.

There are however, no agreed, or formally defined names for the three weeders, particularly the tine weeders. The rotary hoe name is pretty much universal. The three names above in bold are used in this report.

2.2.1. Overview: Vertical vs. horizontal weeding modes of actions (MoA)

While the three weeders may appear to be similar as they do the same thing, i.e., kill smaller weeds across the whole field surface, there are important differences between them, such that they could be viewed as being different modes of action (MoA) if they were herbicides. The differences are sufficient that a farm would benefit considerably from having all three weeders. Indeed having all three weeders could improve weed control sufficiently that the return on investment (RoI) is significant.

The rotary hoe has the biggest difference in it's MoA with the two tine weeders because it has a vertical lifting weeding action compared with the horizontal raking action of the tine weeders. The rotary hoe picks up soil vertically while keeping the spoon tips stationary horizontally in the soil and thus also stationary relative to the crop. In comparison the tine weeders' tines rake horizontally through the soil and crop plants (see the individual weeder chapters for more information). The rotary hoe's niche is thus around crop emergence, both pre-crop emergence (pre-em) and post-crop emergence (post-em) because it has the lowest direct negative impact on the crop (i.e., in the absence of weeds). At the same time it is most effective against cotyledon stage and emerging weeds (see section 2.5 for terminology), which are most common pre-em and post-em, so its use is mainly restricted to this period. In comparison the tine weeders have a more aggressive weeding action and unless used carefully can cause significant crop damage, particularly immediately pre-em and post-em. Thus the rotary hoe has this time period mostly to itself.

Outside this pre/post-em window the more aggressive weeding action of the tine weeders comes into their own. For false seedbeds and weeding immediately post-drilling, the spring, and especially rotary, tine weeders will achieve high to very high levels of weed kill. As the crop grows out of the delicate early post-em stages, the tine weeders can be adjusted to achieve higher levels of selectivity (section 2.9) i.e., still killing a high proportion of weeds while minimising negative impacts on the crop. Spring tine weeders can even be converted into an incontiguous weeder (section 3.16) or for a few 2nd generation weeders (section 3.18.2) have different weeding intensities in the intrarow (crop

row) and interrow, so that delicate crops can still be gently weeded at the same time as having aggressive intrarow weeding. The rotary tine weeder in contrast can deal with harder soils and higher levels of residue than the spring tine weeder, such that the spring tine weeder may be unable to work at all, while the rotary achieves an excellent weeding job.

It is thus all horses for courses.

So, as you read through this report keep the idea in mind that the three weeders have different MoA. That they are different horses for different courses. So you better understand their strengths and weaknesses, as they apply to your crops and your farming system. And therefore best understand which you need and when and how best to use them.

2.3. How weeders kill weeds

The way all mechanical weeders control weeds are commonly described as:

- Uprooting.
- Severing / breaking.
- Burial.

Uprooting means that the weed is still (mostly) intact but the roots have been pulled out of the soil. In dry conditions it is likely to desiccate and die, but if conditions are moist or wet, particularly if it rains, the weed has the chance to reroot and regrow.

If a weed is severed / broken through the hypocotyl (the length of stem below the cotyledon leaves and above the true roots) it is dead. Severing a weed through the roots or the foliage above the first true leaves gives it a chance to regrow, especially where there is sufficient moisture.

Burial can be of intact, uprooted and/or severed weeds. Burial differs from uprooting and severing in that it kills weeds by depriving them of sunlight. It is thus effective whether conditions are hot and dry or cold and wet (Merfield, 2018). For burial to kill weeds they need to have at least 1 cm / ½" of soil completely covering them (Merfield, 2018). The common view is that contiguous weeders mostly kill weeds through uprooting and severing, however, burial can be an appreciable cause of weed mortality especially at higher operating speeds where more soil is thrown around (Parks & Gallandt, 2023).

The three means of killing weeds are not independent of each other. For example uprooted weeds may also be buried (Kurstjens *et al.*, 2000).

In terms of on-farm use, that weeds are killed in three different ways may appear somewhat academic. However, it is important to understand that these differences exist, as weeders vary in the proportion of weeds killed by the three methods. The weeders can also be adjusted to change the proportion of weeds killed by the three methods, for example spring tine weeders can be adjusted to have more of an uprooting effect, digging out weeds, or adjusted to move / throw more soil around so increasing the amount of buried weeds. For the rotary hoe, a sizeable proportion of the weeds are killed by burial from the soil rain, so maximising soil rain though faster speeds is important. Accordingly thinking about how a particular weeder and its adjustments will be affecting the three ways of killing weeds can add valuable insights into weeder setup and use.

2.4. Weed size is everything when it comes to timing weeding

Herbicide application timing is often based on crop growth stages. For mechanical weeding, basing weeding timing on crop growth stage will lead to failure. The golden rule for all mechanical weeding, and especially contiguous weeders, is that weeding **must** be undertaken when the weeds are at cotyledon stage, which is when they are at their weakest (see section 2.5 below for terminology). For each true leaf(s) a weed grows they become exponentially harder to kill. This is because the weeding

action of contiguous weeders need to be sufficiently gentle to not overly harm the crop, so they are not going to kill established weeds that are a similar size to the crop (section 2.9). This contrasts with the interrow weeding tools on a row-hoe which can be very aggressive and can kill large established weeds such as docks (*Rumex* species). For that reason it is vital to check crops on a regular basis to ensure timely weeding, potentially daily around establishment and emergence.

Some people, particularly in N. America, advocate for weeding when the weeds have germinated but before they emerge, sometimes called the white thread stage (see below for terminology). However, as discussed above, burial can be an important part of how contiguous weeders kill weeds. If an unemerged weedling is not directly damaged by a weeder but instead covered by a bit more soil, then it has a chance of continuing to grow through the additional soil and successfully emerge. This will then require a second weeding pass to control these weeds. Thus there is an argument that you should wait to weed until the majority of the weed flush has emerged. However, there is no known research on this topic.

At the same time pre-crop emergence weeding (section 2.19) is most likely to be undertaken when a considerable proportion of the germinated weeds are unemerged. Also, if there is sufficient time and resources an early, extra pass of the weeder, before a weed flush is fully emerged could be considered a good 'insurance policy' — to be sure, to be sure — especially if there is a risk of wet weather preventing or reducing effectiveness at the optimum weeding time. This reverses the above argument that weeding before weeds have emerged could result in some being uncontrolled and thus needing a second pass.

These kind of conflicts highlight why mechanical weed management is as much an art as a science. It is about knowing when to weed as well as how to weed. It is about regularly monitoring the crop and weeding when there is a weed flush. Weeding every weed flush that comes up until the crop is large enough to look after itself. Weeding at cotyledon stage before the weeds get to big, i.e., true leaves. While also taking into account the sensitivity of the crop to weeding, what the weather is doing, the availability of machinery and people to do the weeding…!

If in doubt: weed.

2.5. Weed and crop plant growth stage terminology

In N. America the term 'white thread stage' has been widely used for many decades to describe weeds at early stages of germination and emergence. However, there is no agreed definition. Some use it to describe weeds that have germinated, put out a root and possibly a shoot but not emerged above ground. While others use it to describe weeds that have just emerged, i.e., at the early cotyledon stage when the 'seed leaves' i.e., cotyledon(s) have emerged but before the first true leaf or pair of leaves have appeared. Due to this ambiguity this report avoids the term 'white thread stage' and similar terms such as 'early filament' and uses the following range of terms to describe early weed and crop growth stages:

- **Germinated**: that at least a root has emerged from the seed.
- **Emerged**: that the seed's shoot has emerged from the soil.
- **Established**: the crop has several (pairs of) true leaves, is well rooted and less likely to be killed, e.g., pulled up, by contiguous weeders.
- **Cotyledon stage**: where the cotyledon leaves are unfurled but before any true leaves have been produced.
- **True leaves**: the first true leaf, or pair of leaves, have opened.
- Then the number of true leaves, pairs for broadleafs / dicots, to indicate the size of the weed rather than physical height, as this is considered a better measure of the weeds physiological development and also the size of the root system.

- **Post-drilling**: The time after the crop has been drilled but before germination has started and the root has emerged from the crop seed.
- **Pre-crop emergence (pre-em)**: The time between crop seed germination and the shoot emerging from the soil.
- **Post-crop emergence (post-em)**: The time after the crop has emerged up to around three true leaves / pairs of leaves at which point the crop is considered to be established.

2.6. Contiguous weeders will not kill established weeds but can help manage them

As contiguous weeders work best on cotyledon stage weeds they are manifestly going to be poor at killing established, and especially perennial, weeds. There are however, a few examples where contiguous weeders can be used to help manage established weeds as part of an overall weed management strategy. For example, spring tine weeders can be used as a giant spring-back rake to partly drag shallow creeping weeds out of fields and climbing weeds out of cereals (section 3.14) but, such examples are few and far between.

2.7. Immediate vs. longer term weed management

Integrated Weed Management (IWM) and mechanical weeding as part of IWM, take a long term and system level view of weed management compared with the often shorter term view of herbicide based weed control. The latter focuses on weed control in the current crop and maximising economic returns by maximising weed control to maximise yield. IWM views weed management across the whole farm system over multiple years, with an utterly vital component in annual crops being minimising weed seed rain in current crops to diminish future weed populations. Somewhat ironically, this is best accomplished by achieving high levels of weed control in current crops, particularly around crop establishment, as weeds germinating at this point of the crop's life have the longest time to go to seed. Late germinating weeds rarely contribute to the weed seed rain. Thus particularly true for arable / row crops: going hard and going early with mechanical weed management is not only key for effective weed control to maximise yield in the current crop, but also to minimise weed seed rain and achieve good system level and long term weed management.

2.8. Contiguous weeders are crop row agnostic

One of the major advantages of contiguous weeders for those starting into mechanical weeding from herbicide based systems is they are crop row 'agnostic' (also described as being 'blind' to or 'independent' of the crop rows). Because they weed the entire field surface it does not matter where the crop rows are, how many or how wide the rows are. This also applies to broadcast (random) crops without any rows. A contiguous weeder can in theory be driven any which way over the field, regardless of how it was drilled. This completely contrasts with incontiguous row-hoes where the hoe and the drill must have exactly the same number, spacing and width of rows per bout, which requires considerable standardisation and precise machine setup, plus the use of guidance systems. Consequently contiguous weeders can thus be 'dropped' straight into a herbicide based cropping system without any changes being made to row spacings or any other farm practices.

2.8.1. Matching drill and weeder bout widths

However, in practice it is best if contiguous weeders use the same wheelings / tramlines as the drill to minimise compaction from tractor wheels and avoid unnecessarily driving over crop plants. When following the drill, the drill bout width, and the weeder bout width, really need to match to avoid unweeded strips or over-weeding strips of crop.

Self-evidently, if the weeder is narrower than the drill then the outsides of the drill bout wont be weeded so that must be avoided. If the weeder is exactly the same bout width as the drill there is potential for steering variation to leave narrow unweeded strips, so again best avoided. Therefore, the weeder should be slightly wider than the drill. For row-hoes, having the outside weeder units covering two thirds of the interrow area next to the outside rows ensures maximum overlap with minimum chance of hitting the outside row of the next bout. For contiguous weeders this two thirds overlap of the outside interrows is not as critical. It does not matter if the weeder occasionally 'hits' the crop rows of the next bout, as it is weeding the crop rows already. If a row-hoe hits the next bout it will kill crop plants. Therefore, the overlap could be larger but ideally not much smaller than two thirds overlap to ensure no weeds are missed.

There is also potential for the weeder to be multiple widths of the drill. For example it could be twice as wide, and operating from the same wheelings as the drill, and consequently cover the whole drill bout for the wheelings it is in, and half of the two drill bouts either side, sometimes called 'a bout and two halves'. Or the weeder could cover multiple whole odd numbers of drill bouts, e.g., three or five, while still staying on the drill wheelings. This matching of implements and wheeling is the same as in controlled traffic farming (CTF) (Bloomer & Powrie, 2013).

Having the weeder narrower than the drill, e.g., half its width, would result in extra wheelings and potentially crop plants driven over, which makes no sense. Many arable drills are substantial machines while a weeder the same weight could easily be three times as wide as the drill. You only drill once (hopefully!), while you could weed three to four times, so it makes far more sense to have the weeder cover more than one drill bout so it has the faster work rate.

2.9. Killing the weeds not the crop — selectivity, tolerance, resistance and recovery in post-emergence weeding

Contiguous weeders are mostly used once the crop has emerged, i.e., post-crop emergence (post-em) weeding. The alternative, pre-crop emergence (pre-em) weeding, is undertaken between drilling and crop emergence (section 2.19). The latter only has a narrow time window of a few days to a couple of weeks at most, while, post-em can be undertaken over a period of many weeks, even months, i.e., until the crop is too big / tall for the weeder. Thus most of the time contiguous weeders are used post-em and thus the weeding action is applied to crop and weeds alike.

Consequently, there needs to be sufficient difference in the tolerance of the crop and susceptibility of the weeds such that the weeders mostly kill the weeds and mainly leave the crop unharmed. This difference between the impact of weeding on the crop and on the weeds is called 'selectivity' (Rasmussen, 1992; Rasmussen *et al.*, 2009). Ideally selectivity is high so most weeds are killed and few crop plants are harmed. Further, the ability of the crop to avoid yield loss from weeding in the absence of weeds is called 'tolerance'. Tolerance has two components: 'resistance' and 'recovery'. Resistance is the ability of the crop to resist soil covering and other direct damage from the weeder, and recovery is the ability to recover from the direct weeding impacts such as being covered with soil.

Crops vary considerably in their tolerance due to differences in resistance and recovery, both among species (e.g., cereals such as oats, wheat, barley and triticale) and even among cultivars of the same species (Rasmussen *et al.*, 2004). Resistance is partly dependent on morphology, e.g., upright or prostrate and the crop's height. There is also a large difference in resistance between the rotary hoe and tine weeders. The rotary hoe lifts soil vertically and does not push crop plants over, such that they remain vertical and thus better able to resist soil covering. While the horizontal raking action of tine weeders is much more likely to knock crop plants over, even flattening them while covering them with soil. Then unknown factors determine how well different species and cultivars can recover from being partly buried, e.g., leaves pushing up through the soil covering them.

Selectivity, tolerance, resistance and recovery therefore provide a valuable conceptual framework for analysing how any weeding event is impacting a crop.

As the use of, and research into, spring tine weeders expanded through the 1990s a more scientifically rigorous means of measuring selectivity, tolerance, resistance and recovery was needed. The solution was the concept of 'crop soil cover'.

2.9.1. Crop soil cover (CSC)

Crop soil cover (CSC) is a measure of the amount of soil covering a crop's leaves after weeding. This correlates with the level of harm weeding directly causes to the crop in the absence of weeds, particularly yield loss. Nearly all CSC work to date has been done on cereals using spring tine weeders with exceptions for lupin (Jensen *et al.*, 2004) and peas (Rasmussen, 1993). Thus specific CSC information is most applicable to tine weeded cereals.

CSC was pioneered by Jesper Rasmussen in Denmark in the 1990s and built on by Victor Rueda-Ayala, Roland Gerhards, Martin Weis and many others over more than thirty years (e.g., Rasmussen, 1990; Rasmussen, 1991; Rasmussen *et al.*, 2007; Rueda-Ayala *et al.*, 2011; Rueda-Ayala *et al.*, 2013; Peteinatos *et al.*, 2018; Spaeth *et al.*, 2020; Gerhards *et al.*, 2021; Spaeth *et al.*, 2021).

CSC was developed due to the difficulty, if not impossibility, of specifying and repeatedly setting the operating parameters - tine angle, downpressure and speed - of spring tine weeders to achieve the same weeding intensity between weeding sessions and experimental treatments, particularly in scientific trials. One of the things scientists are fanatical about it is repeatability! This contrasts with herbicides where the dose per ha / acre, nozzle type, pressure, speed, etc., are all easy to calibrate and are thus highly repeatable. Consequently, rather than trying to specify the machine settings, the researchers focused on what was measurable and had a causal link to weeding efficacy and crop harm. The best way of doing this was found to be the amount of soil that the weeder left covering the crop i.e., crop soil cover (CSC). CSC is thus a key determinant of direct negative impact on the crop by the weeder, i.e., yield reduction (beyond not pulling the crop out of the soil) in the absence of weeds. CSC is also a good measure of the level of weed control being achieved as the more soil covering the crop the more intensive the weeding action and therefore the number of weeds being killed.

CSC is determined by measuring the leaf area of the crop canopy immediately before and after weeding. This was initially done with visual assessments and then using image analysis of digital photos, as digital cameras became more common and cheaper. CSC is defined as the percentage of crop leaf that has been buried and calculated as the difference in crop leaf cover (crop canopy) pre- and post-weeding (Rasmussen *et al.*, 2007). For example, if crop leaf cover before weeding is 33% (0.33) and after is 12% (0.12) then CSC = 100*(1 - (0.12 / 0.33)) = 64%.

A considerable number of research trials were undertaken over many years to correlate CSC with crop yield loss in the absence of weeds, i.e., the direct negative impact on the crop. For example Rasmussen et al., (2009) found that oat had the poorest tolerance and largest yield loss with increasing crop soil cover, while barley was dependent on cultivar and year, wheat was second best and triticale had a high tolerance and maintained yield regardless of crop soil cover (Figure 1).

Linking to the CSC research, are studies on intrarow mini-ridger weeders for row-hoes which shows that 1 cm complete burial depth is close to 100% lethal for all plants, regardless of their size (Merfield, 2018). Even when a crop plant is only partly buried mortality can be around 50% (Merfield, 2018). Thus having a crop plant fully buried, even with a shallow amount of soil, is likely to result in significant crop plant losses or at least considerable yield reduction. At CSC of 30% and above crop plants will be increasingly covered by depths of soil that is likely to be causing them mounting harm including yield reductions.

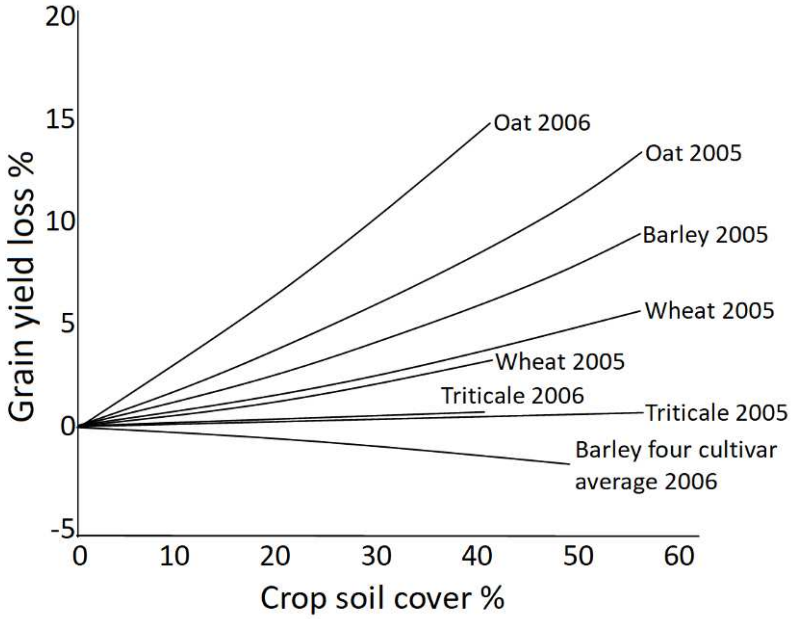


Figure 1. Crop yield loss based on the amount of crop soil cover (CSC) for oats, barley, wheat triticale grown over two years. Based on (Rasmussen *et al.*, 2009).

2.9.2. Using crop soil cover in practice

The standard way to assess the impact of a contiguous weeder on a crop is to check that the crop is still rooted in the soil - that it can't be pulled out easily. If it is still firmly attached, it is considered OK. However, it is clear from CSC research that not being pulled out, is not a good enough assessment of the full impact of a weeder on the crop. Just because weeding does not pull crop plants out but they are covered with too much soil is still likely to be harmful. That harm may not be obvious at the time of weeding, it may only show up in harvest yield. Therefore CSC is an important tool for assessing the impact of tine weeding on cereal crops. The lessons can also be extended to broadleaf (dicot) crops as per the lupin and pea research (Rasmussen, 1993; Jensen *et al.*, 2004).

The challenge is how to assess CSC on-farm. The first step is simple visual assessment - eyeballing the crop before and after weeding - particularly along the edge between a weeded and unweeded strip. This is how researchers starting measuring CSC but it was found to be highly subjective and inaccurate. When digital cameras and computer analysis became available the advantages were so big that the use of visual scoring was discouraged (Rasmussen & Nørremark, 2007). Smart phone apps such as Canopeo www.canopeoapp.com measure crop canopy using green on brown analysis, as well as a range of PC based software that can analyse photos including from drones. Phone based apps have the advantage of being used in the field and giving immediate results that can be acted upon. Images of the crop can be taken either side of a bout edge where the crop is weeded and unweeded and the CSC calculated from the results using the formula CSC = 100*(1 - (weeded crop cover % as a decimal / unweeded crop cover % as a decimal)) as described above.

For cereal crops a CSC of between 10% and 25% is optimal (Spaeth *et al.*, 2020, and references above). Above 30% crop damage and yield loss are more likely to occur so should be avoided unless the crop is very weedy and it is more important to kill weeds than minimise direct crop harm.

An important difference between the automated systems on 3rd generation spring tine weeders (section 3.18.3) and the simple green on brown analysis systems like Canopeo, is that the automated systems are identifying both crop and weeds and only counting the crop leaf area, i.e., subtracting the weeds' leaf area from the total green measurement. If a simple green on brown measurement is undertaken on a weedy area then a ball-park adjustment will be required, i.e., a higher CSC target, e.g., 40% to 50% to take into account both the extra green cover of the weeds increasing the canopy

cover measurement. A higher CSC is also needed because more aggressive weeding is required to control the larger weed populations.

2.9.3. The relevance of soil cover (CSC) for newly emerged crops

Based on CSC and mini-ridger research, the negative impact of CSC on the crop is most likely to be due to the direct effects of soil covering crop plant foliage, rather than the crop being knocked over for example. Therefore CSC is a direct not an indirect measure of the impact of the weeders impact on the crop in the absence of weeds. This points to a potential cause of the negative impacts of tine weeders on newly emerged crops. Small crop plants are easier to cover in soil than tall plants, so it is easier for a tine weeder to cover young crop plants with soil, with commensurate large negative impacts including on yield. Younger crop plants also have less reserves to recover so they may be harmed more by the same CSC as a larger plant. If the tine weeders are used so that soil movement and thus CSC is minimised they potentially will cause considerably less harm for newly emerged crops. This can be achieved by using slow speeds, e.g., less than 4 kph / 2.5 mph, vertical / 90° tine-soil angle and moderate downpressure so the soil is stirred rather than dug up and thrown around. However, once again there is no known research on this so on farm trials are essential.

2.9.4. Only use crop soil cover (CSC) measurements with tine weeders

While the research on CSC has been done using spring tine weeders, as the working action for a rotary tine weeder is sufficiently similar to a spring tine weeder, then CSC percentages are likely to apply to rotary tine weeders as well, so can provide a useful guide. Clearly this is an important area of research to confirm this. As the rotary hoe has a completely different mode of action to spring tine weeders (section 5.5) CSC should not be considered valid for it. Plus, in general as rotary hoes cause much less direct crop plants harm, CSC is also considered less relevant.

As other weeding techniques, e.g., intrarow weeders on row-hoes such as finger weeders and mini-ridgers have not had CSC impacts validated, particularly yield impacts, and as these techniques have fundamentally different effects on crop plants and soil movement, CSC should not be considered valid for them so should not used as a measure of crop impact. This is an issue clearly in need of research.

2.9.5. Selectivity - the importance of crop seed depth vs. weed seed depth

A key factor in the selectivity of contiguous weeders, particularly at early crop growth stages, is that most arable / row crops are large seeded so they are sown deeper e.g., more than 4 cm / 1½", which is deeper than the emergence depth of most weeds, which is less than 2.5 cm / 1" (Merfield, 2015). For small seeded vegetable crops (e.g., carrots and onions) this does not apply as their seeding depth is often less than 2.5 cm / 1", i.e., the same as weed emergence depth. This difference in seed depth for arable / row crops is a significant contributor to selectivity early post-drilling and pre- and post-crop emergence. Simply the weeder is operated shallower than the crop seed depth, but as deep as (most) of the weeds seeds. Thus the weeder is tilling the soil the weeds are emerging from, and where their roots are, but not the soil the crop seeds and their roots are in, hence achieving high selectivity. It is therefore critical to carefully check the depth of both emerging weeds and the crop by digging some holes, rather than just assuming, or worse, guessing! As discussed in section 2.11 increasing sowing depth can be an important tool for increasing selectivity, particularly pre-crop emergence and early post-crop emergence.

2.9.6. Conclusions on killing the weeds not the crop

The research on CSC, selectivity, tolerance, resistance and recovery shows that the common view that as long as the crop is still well rooted after tine weeding is insufficient to decide if the crop OK after weeding. If more than 30% of the crop is covered with soil then tine weeder settings should be changed to reduce CSC to below 25% otherwise the risk of yield loss becomes too high.

With the advent of automated systems for adjusting harrowing intensity (section 3.18.3) coupled with the rapid expansion of mechanical weeding, it is hoped that more tools will be developed that allow farmers and growers to measure their CSC. Also, that research determines optimum CSC for a much wider range of crops and weeding tools while taking weed pressure into account. In the mean time, it is important to be aware that just because the crop is still anchored to the ground, it is not a good enough measure of a weeders impact on the crop, particularly yield, and that CSC needs to be taken into account.

2.10. Increased sowing rates

A common rule of thumb in organic farming where contiguous weeders are being used on arable / row crops (i.e., not vegetables) is to increase the sowing rate by around 10% to compensate for some crop plants getting killed by the weeders. Another advantage of increased sowing rates is that it often makes the crop more competitive, particularly by achieving greater ground cover quicker. There is however limited research on increased sowing rates used in conjunction with contiguous weeders. How effective and economic they are likely to be will depend on the crop species and even cultivar, the type of weeder, how it is used, as well as soil and weather conditions. Scientists will never be able to provide answers to all those combinations, so, again, it is one of those techniques that you need to undertake your own trials on (section 2.7).

2.11. Increased sowing depth

A key factor in the selectivity of contiguous weeders is that most of the drilled crops are large seeded so they are sown deeper e.g., more than 4 cm / 1½" deep, which is deeper than the emergence depth of most weeds, which is less than 2.5 cm / 1" (Section 2.9.5) and (Merfield, 2015). The weeding depth must be shallower than the sowing depth, otherwise the risk of the weeder hitting and damaging the crop seed or pulling the crop out by the roots increases immensely. Therefore increasing sowing depth, increases the vertical distance between the crop seed and the weed seeds, so that weeding can be deeper without increasing the risk of crop damage (too much). It can also be a valuable tool for improving selectivity and/or being able to target larger seeded, and deeper emerging weeds, including crop volunteers. Sowing deeper may also result in the crop taking longer to emerge which may be valuable in increasing the pre-em weeding window (section 2.19). However, all the usual agronomic caveats with increased sowing depth apply, such as reduced emergence, so, going too deep will be detrimental. So, yet another variable that would benefit from on-farm trials (section 2.7).

2.12. Trial and error - learning by doing

Aside from this report, online videos, manufactures' information and talking with farmers and growers already using mechanical weeders (see section 7) the best way to learn how to use contiguous weeders is trial and error i.e., learning by doing. There are so many combinations of crop species, cultivar, soil type, soil conditions, weed flora, etc., that it is impossible for researchers to provide the kind of prescriptive 'recipes' that they do for herbicides. That is also why there are so many 'qualifier statements' such as 'probably' in this report. Indeed contiguous weeding pretty much proves the rule 'there's an exception to every rule'! There is simply not enough definitive knowledge, at least recorded knowledge, about contiguous weeders for definitive statements to be made about how to use them, and with the many combinations of variables there never will be.

Thus, skill and experience, i.e., the art of mechanical weeding (section 1.4), are a vital part of the mix. So just 'playing' with your specific weeder(s) in your crops and soil against your weeds is the best way to become proficient. Taking a more structured approach than just suck it an see, will help you more quickly build experience . For example, for a given crop try different speeds, or level of

aggressiveness, clearly marking in the field where you tried the different settings. Just checking the crop immediately post-weeding, i.e., that it has not been pulled up, and/or completely buried is not enough. As per section 2.11 on selectivity and crop soil cover (CSC), different crop species, even cultivars within a species can respond differently to how well they resist being covered with soil and also how well they recover. Thus the impacts on the crop from different weeder settings may well flow though all the way through to final harvest yield. So, ideally different treatments need to be followed through to harvest.

As following through to harvest is important, where combine harvesters have yield monitors, consideration should be given to doing 'strip trials' where different treatments are done in strips along the full length of the field, and then the yield of that strip is measured with the combine. In a perfect scenario individual treatments would be replicated and assigned to random strips so that the results can be statistically analysed. At the same time agricultural statisticians (biometricians) are often critical of even randomised and replicated strip trials as the layout can still create biases in the data. However, for farmer trials, this is a case of perfection getting in the way of good enough, particularly considering that yields vary by ± 20% field-to-field and year-to-year. So you are looking for yield differences among treatments of more than 10%, anything less is likely to be random variation.

There is also potential to cause considerable crop harm, including complete loss of yield, with mechanical weeders. Trials should thus only be done on small areas - small enough that complete crop loss will not be financially damaging. Do not bet a whole field, let alone the farm, on trial work.

For the kinds of trials described above, it is also impossible to separate out the positive impact of the weeding on reducing weeds and the negative direct impact on the crop from weeding (e.g., soil covering). Clearly this is going to depend on how many weeds there are to start with! Thus some 'eyeball' assessment and farming gut instinct is required to decide what the relative contributions are.

It is also worth getting all the farm staff who will be using the weeders to be involved in trial work, especially in the early days when mechanical weeding is new to everyone. Having more boots and hands on the ground can significantly speed up manual weeder adjustments like depth wheels. Having more eyes and brains on the ground also makes for superior collaborative interpretation of the immediate results and better, faster learning all round.

2.13. Weeding across crop rows

In the early days of contiguous weeding farmers and researchers tested weeding across the crop rows, typically at 90°, with the aim of to improving intrarow (crop row) weed control (e.g., Rydberg, 1994; Pardo *et al.*, 2008; Rasmussen *et al.*, 2008). However both farmer experience and research found there was little or no improvement in weed control, and sometimes it was worse. In some instances crop yield was also reduced, potentially due to increased crop damage from tractor tyres driving across the crop row and/or increased crop soil cover (CSC, section 2.9.1).

In addition as around three quarters of compaction from tractor tyres occurs in the first pass, weeding across the rows adds significant extra compaction to the field. With the utterly clear benefits of compaction management approaches like controlled traffic farming (CTF) and RTK GPS autosteer, weeding from the drill wheel tracks is the preferred approach and weeding across crop rows is best avoided.

2.14. Soil and weather conditions

These are some general comments and overview of the impact of soil and weather conditions on contiguous weeders and mechanical weeding as a whole. Greater and specific details are given in each weeder's individual sections.

2.14.1. Weather

There is a common view that mechanical weeding only works in hot, dry conditions, both weather and soil. This is completely incorrect. It is true that the highest weed kill will be achieved in hot, dry conditions but high levels of weed kill can still be achieved in cool and damp conditions. People even weed when it is raining! Particularly for contiguous weeders that need to target weeds at the cotyledon stage it is often much better to weed on time in sub-optimal conditions, that wait for hot weather and dry soil and let the weeds get too big.

2.14.2. Soil moisture

As for weather, while dry friable soil will result in the highest possible weed kill, moist, even wet soils can still be mechanically weeded. There are clearly limits, particularly as the soil reaches a plastic state as the weeders will end up just cutting through the soil and not moving soil crumbs around. Even then, the likes of the rotary tine weeder may still kill weeds, though potentially making a mess of the soil surface and coating crop plants in mud.

2.14.3. Soil tilth

Soil tilth varies in its impact on weeding efficacy among the three weeders and more details are given under each weeders section. In general spring tine weeders need a reasonably loose tilth as their ability to penetrate un-tilled and/or hard packed and capped soils is limited. In comparison rotary tine weeders push the end of their tines into the soil so have greater penetration ability so can cope with denser soils. Rotary hoes punch vertically downwards into the soil, so can work in harder soils, and they are commonly used to break soil caps. However, if the soil is not friable, and this applies to rotary tine weeders as well, while they can penetrate and break up the soil the results are likely to produce large clods and/or slabs of crust, resulting in unsatisfactory weed control and harm crop plants.

2.14.4. Stones and clods

Another common misconception is that mechanical weeding, particularly contiguous weeders, can't be used in stony soils. As Figure 14 shows high levels of weed control are possible even in very stony soils. The flip side is if stony soils are likely to harm the weeders. The spring tine weeder is mostly impervious to damage, with the exception of accelerated wear. Rotary tine weeders may get stones and clods stuck between the tines, and some weeders have clearing mechanisms to dislodge stones and residues that get stuck on the tines. For rotary hoes, stones will considerably accelerate spoon wear, which as the spoon is critical for the weeding action means that rotary hoes are best suited for stoneless soils or those with a only a few and smaller stones.

2.14.5. Residue

Coping with residue is another area of underestimation of contiguous weeders. Rotary hoes can cope with high residue levels and there are even high residue versions (Figure 30). Rotary tine weeders can work in medium residue levels. Even spring tine weeders can work in moderate residues if the residues are not too long, otherwise they will act as a giant rake!

2.15. Contrasting and thus complimentary weather windows for herbicides and mechanical weeding

The weather conditions for spraying herbicides and mechanical weeding are often quite dissimilar. Herbicides can't be applied if it's too windy (due to spray drift) and in some cases if there is not enough wind. Hot conditions can also be a problem causing volatilisation and cold can rule out application as well. Hot windy weather is therefore an anathema for spraying herbicides, but, this is the very best time to go mechanical weeding! In contrast very wet soils would impede mechanical

weeding, but if it is not raining and the weeds are dry, herbicides can be used instead. These contrasting weather windows mean that where both herbicide and mechanical weeding are available, the weather window when weeding can be undertaken is much larger. It is thus of considerable value to be able to choose between mechanical weeding and herbicides to suit the conditions and reduce the risk of failed weed management because the weather was not cooperating with just one approach.

2.16. If at first you don't succeed, try, try again!

A critical difference between many herbicide applications and mechanical weeding, is there is no limit on the number of applications. For many herbicides there are limits to how many applications can be made if the first application fails to work as expected. These include legal limits, harvest intervals, where applying the same herbicide twice would double the applications rate, which may then harm the crop, etc. In contrast, if a mechanical weeding pass fails, or does not achieve the desired result, then just try, try again until the desired level of weed control is achieved. There are no barriers to repeat treatment, apart from time and economics. This includes using mechanical weeding where herbicides have failed to achieve sufficient weed control (see also section 2.25).

2.17. Don't over-weed at later crop growth stages

A consistent pattern coming out of spring tine weeder and rotary hoe research is that multiple weeder passes as the crop gets larger e.g., BBCH stage three, often have significant, e.g., 10% to 30% reductions in yield across a range of crops. This contrasts with farmers and growers who say they like to keep weeding even as the crop gets larger. The research indicates that one, two and three passes at early crop stages, including pre-emergence weeding has little or limited impacts on yield. But, when additional passes with contiguous weeders are made as the crop gets larger, e.g., taller than 10 cm / 4", then considerable yield losses can occur. This indicates that producers are potentially loosing significant yield when they continue using contiguous weeders as the crop is getting larger.

Other research using thermal weeding at crop growth stages beyond the first month or so of a crops life, particularly as the crop moves to reproductive stages, also have considerable negative impacts (Merfield, 2006, page 93 and references within). Likewise, selective thermal weeding at early crop growth stages can have no impact on yield (Dastgheib *et al.*, 2010). Grazing cereal crops early on can increase tillering and thus yield and there are even cultivars, e.g., cv. 'DoubleTake' Triticale, bred for grazing over-winter. There thus appears to be a general pattern that crops can withstand even total defoliation when young, but, as they grow, and particularly as they move towards reproductive growth, damage to the foliage results in significant yield reductions, even total yield loss.

There are thus good reasons to believe that using contiguous weeders beyond early crop growth stages is detrimental to yield and should be avoided. The best approach is once the crop has passed through the early growth stages, to move from contiguous weeders to incontiguous row-hoes, including using intrarow weeders e.g., ridging systems and finger weeders. As most intrarow weeders only interact with the crop plants' base, not the entire foliage, it is considered likely to have a smaller or no direct negative impact compared with a contiguous weeder (also discussed in section 6). This progression from contiguous to incontiguous weeders as the crop grows is also common among experienced organic arable / row crop farmers, who are wholly reliant on mechanical weeding.

So while "if in doubt: weed" is still fundamental advice, particularly around crop establishment, using contiguous weeders on larger crop plants may be inflicting a significant yield penalty and that incontiguous row-hoes are the best option once the crop gets larger.

2.18. False seedbeds

A false seedbed is defined as soil that is tilled / cultivated ready for planting, but planting is delayed, allowing a weed flush to emerge. The weed flush is then killed by very shallow, less than 3 cm / 1" deep, tillage / cultivation and then the crop is planted (Merfield, 2015). False seedbeds are of the utmost importance in achieving good weed management in cropping systems using tillage and thus should be used whenever possible (Merfield, 2015).

Spring and rotary tine weeders are good machines for undertaking false seedbeds, particularly at scale Two passes can be made (often in opposite directions) to maximise weed kill. See Merfield (2015) for full details on false and also stale seedbeds.

2.19. Pre-crop emergence weeding (blind weeding)

Pre-crop emergence (pre-em) weeding is a technique from the pre-herbicide era, where a contiguous weeder is used between drilling and crop emergence to kill weeds, including weeds that have not emerged.

Pre-em weeding is commonly called blind weeding / harrowing, but as noted in the introduction, the term 'blind' is used in multiple different ways within mechanical weeding, including being a synonym with contiguous weeders i.e., blind weeders / blind weeding. Due to the term 'blind' having multiple different meanings, and also not being a technically accurate description of the technique, this report uses the term 'pre-emergence weeding' instead. This also aligns the technique with standard herbicide terminology where a pre-emergence herbicide is one that is applied to the soil (a residual) before the weeds have emerged (and ideally before they have germinated) and typically before the crop has emerged / germinated as well. 'Pre-emergence weeding' as a term is also commonly used in European research, while 'blind weeding' is very seldom used.

Weeds that emerge with the crop, and which are controlled by pre-em weeding, are often the weeds that are the most competitive against the crop and responsible for the greatest yield loss. They are also the weeds most likely to produce seed, as they have the longest time to grow, flower and reproduce, thus replenishing the weed seedbank and creating bigger weed problems in the future. Consequently killing weeds that emerge with the crop is often the most important weeding operation.

Before herbicides, pre-em weeding was considered an essential part of weed management as it can control weeds that are likely to emerge with the crop (Robbins *et al.*, 1942). Many current farmers using mechanical weeding and companies manufacturing / supplying weeders are also strongly promoting pre-em weeding (often calling it blind weeding).

Thus, the practical and scientific evidence for the vital importance of pre-em weeding is totally clear.

Typically pre-em weeding is done when the crop seed has produced a root but before the shoot emerges. This is because the emerging shoot is often brittle and easily broken killing the plant, and it is growing up through the soil layers that the weeders operate in. Prior to shoot emergence tine weeders are the better weeder option than a rotary hoe as they have a significantly higher weed kill than rotary hoes. Also their working depth can potentially be more accurately controlled, depending on the specific design of the weeder used.

However, once the shoot has started to emerge everything changes. For cereals there is some leeway past shoot emergence as the shoot has some flexibility. However, broadleaf crops, and especially the likes of beans (e.g., soya) at the hook stage, are considered highly vulnerable to damage. Due to their weeding action, tine weeders are best avoided at this stage as they are considered likely to damage the crop's emerging shoots. However, there are reports from farmers, and examples from research, where pre-em crops have been successfully tine weeded without harm. This may be due to how the

crops were weeded, i.e., gently vs. aggressively, see section 2.9.3 for more discussion. Rotary hoes are generally considered OK to use post shoot emergence, though with lower downpressure and slower speeds. With this conflicting advice, assume crops are likely to be harmed, but may potentially be OK to be weeded, so again, on-farm testing is required to confirm if weeding is safe for each crop species at different weeding intensities.

While, pre-em weeding is typically done post crop root emergence but pre shoot emergence, as this gives weeds time to germinate, some farmers, particularly in N. America, will start weeding just a few days after drilling, i.e., before the crop has even germinated. This may be overkill - and a suboptimal use of time and machinery, but, it may also be a useful 'insurance policy' to control the first weeds to germinate.

2.20. Pneumatic seeders

Most manufacturers of spring and rotary tine weeders offer a pneumatic seeder option and a few rotary hoe manufactures do the same. Having a seeder on a contiguous weeder considerably increases their usefulness.

Pneumatic seeders blow seeds down tubes that broadcast the seed in front of the tines. They can thus be used instead of drills for sowing the likes of pasture and service (cover) crops. However, their greatest value is in sowing intercrops such as living mulches, under sowing and relay cropping into existing cash crops as part of the final weeding pass (Merfield, 2023b). For example, a crop is weeded with multiple passes and then on the final pass the intercrop is sown using the pneumatic seeder. The intercrop generally cannot be sown before the final pass as it will be killed by the later weeding passes unless it is robust enough.

While a small number of rotary hoe manufactures offer seeder units there is no known research into how effective they are at seed incorporation. There are also no know comparisons with either tine weeder. As the tine weeders have a much greater soil mixing action compared with a rotary hoe they would be expected to incorporate seed more effectively. Also as rotary hoes are chiefly effective against cotyledon stage weeds they are mostly used at young crop growth stages while service crops are typically sown into a cash crop at later growth stages, when typically a tine weeder would be used. Thus there is something of a timing mismatch, but, if a rotary hoe is the only weeder available using it to seed as part of a late pass through a cash crop will still be valuable and likely achieve a better stand than just broadcasting the seed onto the soil surface.

As pneumatic seeders are broadcast seeding, all the usual caveats of broadcasting vs. drilling seed apply. For example, the strike rate is typically lower, often much lower, than drilling as only a small percentage of seed ends up at the optimum planting depth, most is too deep and too shallow. Higher seeding rates are therefore typically used, all the way up to doubling rates. An advantage of broadcasting pasture rather than drilling is a more even (random) cover of plants is achieved, which can help the pasture out compete weeds in the first years by eliminating the bare interrow space from drilling.

2.21. Fertiliser application and incorporation

The pneumatic seeders discussed above can also be used for fertiliser application and some weeder manufactures have dedicated fertiliser hopper systems, e.g., front three point linkage bulk hoppers, that utilise the pneumatic seeder hose distributor system for applying fertiliser. There are two key benefits of applying fertiliser in this way.

Pneumatic systems achieve much more even distribution, especially over larger working widths, than ballistic systems, such as spinning disks, especially for mixed fertilisers where the different fertiliser materials have different ballistic properties.

The fertilisers are partly incorporated into the soil, which for fertilisers that need good soil contact for effective release, and particularly nitrogen fertilisers, such as urea, that can loose nitrogen to the atmosphere as ammonia, having the fertiliser at least partly incorporated can be of significant value.

And if you are weeding and fertilising at the same time, that is two jobs in one pass, with commensurate cost savings.

2.22. Visibility of working area

All contiguous weeders can experience problems, for example spring tine weeders can block with residue and tines can hook (section 3.17), rotary hoes and rotary tine weeders can have stones, clods and residue stuck on and between tines potentially stopping them rotating. Therefore being able to see the working area from the tractor seat is important to be able to spot such issues and fix them before they damage the weeder or crop. However, working area visibility varies between weeder types and designs, with the main toolbar often being the thing that blocks view the most. So, checking working area visibility is an important part of assessing a weeder for purchase.

Particularly for larger machines, having cameras linked to an in-cab display is proving valuable for keeping an eye on weeders and other machinery.

2.23. Variable widths on folding weeders

For larger width contiguous weeders with hydraulic folding, especially those with multi-part folding, some can be used partly-unfolded allowing different working widths to match different crop planting configurations. For example a 12 meter weeder can have the outside two sections folded into make an 8 m working width, or have all sections folded to give a 3 m working width.

Some designs also permit asymmetrical unfolding, for example if a field edge does not match up with the full width, then that side of the weeder can be folded up.

2.24. Arable vs. row crop vs. vegetable cropping systems — contiguous vs. incontiguous

Deciding where to start with mechanical weeding differs significantly for arable, row crop and vegetable systems.

As the weeding action of contiguous weeders is applied to crop and weeds alike, the crop needs to be tough enough to survive the weeding action. Arable / row crops such as cereals, maize / corn, soybeans and oil seeds are generally pretty tough and can tolerate contiguous weeding, at least once established. Indeed, contiguous weeders were developed for weeding arable crops.

Arable crops are typically grown in narrower rows, e.g., 15 cm / 6” creating less interrow space meaning they are less suited to incontiguous weeders such as row-hoes. They also typically have higher crop plant populations and loosing a few crop plants has no impact on yield and profit.

Row crops (as it says on the tin) are grown on rows, mainly wide rows greater than 24” / 60 cm. Crop plant populations in the rows are also generally high, so the loss of a few plants is of no or minor impact.

Vegetables are a different matter. Most are small seeded and where they are direct seeded contiguous weeders generally cannot be used at until the crop is well established. Transplants also need to be well enough rooted to not be ripped out before a contiguous weeder can be used. Vegetables also obviously vary widely in their foliage morphology so the impact of a contiguous weeder needs to be determined at the species level. Some crops are well suited to contiguous weeders such as leeks, which are tough(ish) and have a single upright ‘stem’. Others such as lettuce

have thin, prostrate leaves which will be easily damaged by the weeders, especially at larger growth stages. Many crops are grown at row spacings wider than 15 cm / 6". Crop populations are often critical for ensuring uniform crop size, compact harvest time, and profitability. Loosing even a few crop plants can thus be costly.

Thus, for arable systems contiguous weeders are the typical starting point as they are a drop in replacement for broadcast herbicide application as no changes to the production system, e.g., row and bout widths, is required (section 2.20). In comparison using an incontiguous weeder, i.e., row-hoe, means that the drill and row-hoe have to match perfectly (section 2.20 and Merfield (2026a)) so introducing row-hoes to arable systems can entail a lot of work to get drill and hoe to match. However, for arable farms where mechanical weeding is a significant part of weed management, having both contiguous and incontiguous weeders is important for effective overall weed management.

For row crops, the wide row spacing makes them ideally suited to row-hoes. However, contiguous weeders are still widely used in row crops, particularly pre-emergence and early crop growth stages due to them weeding both in the intrarow (crop) row and interrow. They are most common in N. America where row-hoes with intrarow weeding tools are uncommon and mostly interrow hoes / cultivators are used with limited intrarow weed control, mostly intrarow soil ridging from the interrow ducksfoot and sweep blades (Merfield, 2026a).

In vegetables, contiguous weeders cannot be used on all crops, and where they can, often only once plants are well established. In contrast, row-hoes can be used on all crops at a wide range of, even all growth stages, with intrarow tools used, or not used, depending on crop and growth stage. Row-hoes are therefore the starting point. At the same time, it is impressive just how many vegetable crops contiguous weeders can be used on, particularly when used with care. For example, young lettuce, once firmly rooted can be tine weeded as any damaged leaves will senesce before the plants reach maturity. Thus having a row-hoe as the primary weeder, but, being able to use a spring tine and/or rotary tine weeder(s) in some crops is a valuable approach. However, rotary hoes are considered to have limited value in vegetable systems, due to the lower levels of weed control and the large amount of soil that rains down on the crop, which would cause crop contamination and market rejection for many crop species. However, there are a few vegetable growers successfully using them.

2.24.1. Which contiguous weeder to start with for arable, row crops and vegetables

With three different contiguous weeders to choose from often the question is: which one should I buy first? This depends on your cropping system. This is also not an either or question. For arable / row crop systems, particularly for larger operations, having all three weeders will give the greatest flexibility due to the different modes of action of the weeders (section 2.2).

In arable / row crops the mostly likely first choice will be a spring tine weeder as they have been around for 60+ years, there are lots of manufactures and are often available second hand. The next question is then: 1st or 2nd generation spring tine weeder? (section 3.18). There is no simple answer as there are a range of pros and cons for each, but where mechanical weeding is being introduced into a herbicide based weed management system as a replacement for one or two herbicide applications in a few crops, then a 1st generation weeder will be cheaper, more available second hand, and will be a good tool to learn on. Where mechanical weeding is going to be doing a greater proportion of weed management then a 2nd generation weeder, especially for machines wider than say 6 m / 12' could be the better option due to the quicker and easier adjustment that can also be done on the move.

It is then a close call if a rotary hoe or rotary spring tine weeder would be the best machine. On soil textures where capping is a problem, particularly around crop emergence, then a rotary hoe is potentially the next choice. Otherwise a rotary tine weeder could be the better option as it has a larger weeding 'window' so will deliver a greater amount of weeding overall. Location will also be a decider: in N. America rotary hoes are the most common contiguous weeder so there are lots of machines, including second hand, plus farmer and research expertise to call on. In Europe both weeders are equally available.

For vegetable crops, where a row-hoe is the primary weeder, a spring tine weeder is most likely to be the first option. A 2nd generation weeder is likely the better option due to the higher downpressure precision that can achieved, allowing crops to be gently weeded at more sensitive growth stages. Only when the combination of a row-hoe and spring tine weeder combination have been fully utilised, would it be worth considering a rotary tine weeder. An exception to this is where capping is a common problem, then a rotary tine weeder would be more valuable. As noted above, a rotary hoe has a very limited role in vegetable production systems.

2.25. Integration with herbicides

With increasing herbicide resistance and no reason for it ever abating, loss of existing chemistry combined with very limited new chemistry, increasing numbers of farmers and growers are integrating mechanical weeding into herbicide based weed management systems. Integration of herbicides and mechanical weeding is thus a key first step into full Integrated Weed Management (IWM). Beyond combating herbicide resistance producers are finding multiple benefits of integrating mechanical weeding, such as:

- Reducing herbicide phytotoxicity, particularly at early growth stages, and thus increasing yield.
- Reducing costs as mechanical weeding can be cheaper than herbicides.
- Breaking up soil crusts.
- Mineralising some soil organic matter to release nutrients, particularly nitrogen.
- Gives a wider weather weeding window as the right weather for spraying herbicides and the best weather for mechanical weeding are often highly complementary.
- Etc.

Therefore, integrating mechanical weeding and herbicides can improve weed management, including widening the weeding weather window (section 2.15) and increase profitability. At the same time there is limited research (less than 50 papers) and practical experience in integrating herbicides and mechanical weeding, a number of which are from the dawn of the herbicide era using herbicides that are now banned globally.

The most obvious and widely used approach is band spraying the intrarow (crop row) and hoeing the interrow. This just splits the field into alternating strips of standard herbicide and standard mechanical weed management. Success is pretty much guaranteed as nothing new is being done. Compared with broadcast spraying, band spraying considerably reduces the total amount of herbicide being used and number of weeds exposed to herbicide, which is a key part of herbicide resistance management. It also can save money, particularly for more expensive herbicides. It also leverages the most effective form of mechanical weeding, i.e., interrow hoeing, and the power of selective herbicides. Band spraying pre-emergence residuals which control weeds in the pre-crop emergence and early post-crop emergence stages when mechanical weeding is the most difficult, and then using mechanical weeding in the intrarow (crop row) as the residuals wear off, is considered to be a particularly powerful technique. The high level of reliable weed control and being easy to understand, is why band spraying and interrow hoeing is the most popular form of integration. It is also why increasing numbers of interrow hoe manufactures supply band spraying systems for their

hoes. Making your own band spraying system is also not complicated. Around half the research on integrating herbicides and mechanical weeding has focused on band spraying.

The next step in integrating herbicides and mechanical weeding is using a contiguous weeder as a direct substitute for a broadcast foliar herbicide, i.e., against emerged weeds. For example, an established crop could be tine weeded instead of applying a selective foliar herbicide. As the mechanical weeding and foliar herbicides are being applied in a sequence, there are limited ways for them to interact, either positively or negatively. Potentially weeding could cover the crop and weeds in soil dust and reduce efficacy of a broadcast herbicide applied shortly afterwards, but ways for them to negatively interact are considered few and far between. This is also considered a low risk approach, due to the lack of interaction, and if either herbicides or mechanical weeding don't perform as required, then, a repeat treatment, either herbicide or mechanical can be undertaken.

The most complex and interesting way of integrating herbicides and mechanical weeding is considered to be residual herbicides (i.e., applied to the soil) and contiguous weeders. This approach has the least amount of research. Root absorbed residuals often need to be mechanically incorporated or washed into the soil to reach the weeds' root zone. So theoretically, mechanical soil disturbance, particularly by tine weeders could be a good, even the most effective means of incorporation. In direct contrast, shoot absorbed residuals need to form a skin / cap at the soil surface, e.g., top 1-2 cm / ½", that the weeds' shoot grows through picking up the herbicide. Logically using a contiguous weeder on soil with a herbicide skin will destroy the skin and render the herbicide ineffective. While logically sensible, the limited research means that once again, you will need to undertake your own trials (section 2.10).

2.26. Soil health impacts

There are often concerns that mechanical weeders have (significant) negative impacts on soil health because they disturb the soil. Such concern is wildly overblown.

For both physical (mechanical and thermal) and chemical (herbicides) weed management, by far the largest negative impact on soil health is the act of killing weeds (Merfield, 2022). This is because the primary driver of soil health is a large biomass and diversity of living plant species producing root exudates that directly feed soil microbes (Merfield, 2026b). The primary function of physical and chemical weed management is to reduce plant biodiversity and biomass (i.e., eliminate non-crop plants). Therefore the primary function of physical and chemical weed management is responsible for the biggest negative impact on soil health (James & Merfield, 2023) and other environmental aspects such as biodiversity. Accordingly, the direct negative impacts on soil from mechanical weeding has a vastly smaller negative impact than the primary function of killing weeds. This is why agriculture and horticulture need to move to Integrated Weed Management (IWM) maximising ecological weed management to minimise the overall negative impacts of weed management (Merfield, 2026b).

For production systems that use tillage / cultivation (i.e., not no-till / direct drilling) the amount of soil disturbed by weeding is much smaller, and disturbed far less, than by the preceding tillage. Thus tillage will be doing far more direct damage to soil health than mechanical weeding. Accordingly if there are concerns about soil health, those concerns should be focused on tillage first and the impacts of mechanical weeding second.

For no-till systems, mechanical weeding will be disturbing more soil than drilling. But the disturbance is still small. The reduction in plant biodiversity and biomass from all forms of weed management will still cause far greater soil harm. And just because no-till does not till the soil does not mean there is no damage, for example there are increasing concerns about compaction in no-till (Keller *et al.*, 2025) which has massive negative soil health and yield impacts. For that reason, using mechanical weeding in no-till does not have to be viewed as going against all that no-till represents. Plus, considering the

challenge of grass weeds in no-till, particularly herbicide resistant grasses, using mechanical weeding is going to be of increasing importance.

At the same time many of the claims made by weeding machinery manufacturers and retailers about mechanical weeder's soil health benefits, such as improving aeration, are often considerably overstated or just plain wrong. Most people making such claims do not have soil science expertise, they are engineers and sales people. Treat all such claims with considerable caution.

2.27. Energy use

Another common concern about mechanical weeding is the amount of energy used. However, when the embodied energy in herbicides (i.e., the energy required to manufacture and distribute them) is taken into account mechanical weeding can use an order of magnitude less energy, even more, than herbicides (Figure 2), (Kaufman & Schaffner, 1982; Coleman *et al.*, 2019, 2020; Bloomer *et al.*, 2022).

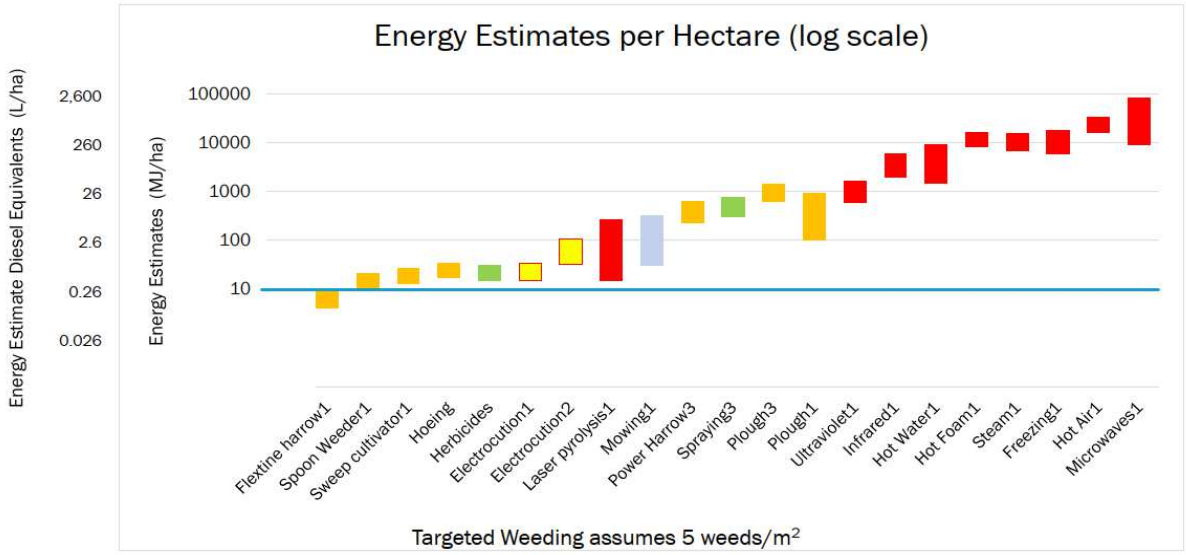


Figure 2. Weed control: relative energy requirements, note log scale on Y / value axis. From (Bloomer, 2023).

Thus energy consumption by mechanical weeding is another area of concern that is widely overstated. Indeed, if energy consumption for weed control was a key driver, then mechanical weeding would be a priority.

3. Spring tine weeders

3.1. Key points

- Spring tine weeders (STW) consist of thin springy tines akin to a giant garden spring rake.
- STW evolved from tillage harrows with the modem form invented in 1952.
- Weeds should always be targeted at cotyledon stage but up to three sets of true leaves may be able to be killed.
- Crop plants are widely considered susceptible to STWs once the shoot has emerged from the seed until there are two to three true leaves However, with careful use even these stages may be able to be weeded.
- STWs mostly kill weeds through severing and uprooting but burial can be a significant contributor, especially at higher speeds and with deeper tine depths that cause increased soil throw.
- The angle of the tines to the ground is a key adjustment, pointing forwards, vertical or backwards. All the principles of tine angle from tillage / cultivation apply with forward angled digging in and backwards being forced out of the soil.
- Downpressure, i.e., the force that the tines are pushed into the soil, is the second key adjustment and just as for tillage, the more downpressure the deeper the tines will go, which mostly increases weeding aggressiveness and amplifying the other adjustments.
- Forward speed is the third adjustment and varies from a crawl to faster than a run. As for downpressure, increasing speed generally increases weeding aggressiveness, particularly increasing soil throw and thus crop soil cover (CSC) and also amplifying the other adjustments.
- With the three adjustments all interacting, a very wide range of crop-weed-environmental conditions can be accommodated from very gently 'tickling' delicate crops with newly emerged weeds to very aggressive, almost tillage like, intensity on really tough crops in difficult soil conditions and/or larger weeds.
- Soil tilth needs to be reasonably friable for weeding to be effective as STWs cannot penetrate hard soil or thick caps.
- While hot drying weather is ideal weeding can still occur in cooler moist conditions.
- Stones and clods reduce weeding efficacy however, it is nearly impossible to damage a STW as the tines simply skip over obstacles.
- Residue can be a challenge, shorter stiffer residue will flow through the tines, especially at slower speeds, but longer flexible residue will catch on the tines thus the weeder will act as a rake.
- Spring tine weeders, especially 2nd generation, can be used to weed on ridges
- Crops up to knee high can potentially be weeded, but at much slower speeds but with the caveat that they may reduce yield even though the crop appears OK.
- STWs can be turned into an incontiguous weeder by tying up the tines over the crop row. Some 2nd generation weeders have the ability to have different downpressure for the intrarow and interrow. This allows crops at delicate stages to be weeded when it would otherwise be impossible.
- There are three 'generations' of spring tine weeders:
  - 1st generation weeders are the original design with mostly manual adjustments.
  - 2nd generation weeders have independent downpressure systems so the downward tine force is the same regardless of their vertical position. Changing downpressure is mostly done remotely / from the tractor seat. This has multiple advantages, particularly being able to change weeding intensity on the move.
  - 3rd generation weeders are moving from research to commercialisation and are based on computer vision systems that measure crop soil cover (CSC) on the fly and automatically adjust weeding intensity to keep CSC below damaging thresholds.

3.2. Spring tine weeder design

Spring tine weeders are based on long, ~40 cm / ~16", thin ~6-8 mm / ~¼" round steel tines, with a bend / 'hook' at the end (Figure 3). The tines are dragged through the top few centimetres / inch of soil. The tines are sprung so they vibrate when moving through the soil and can move out of the way of obstacles such as stones. The tines are mounted on a weeding frame consisting of a series of bars, across the direction of travel, and staggered so the horizontal distance between tines on different rows is about 2 cm / 1" such that as much as possible of the soil surface is disturbed (Figure 3).



Figure 3. Hatzenbichler spring tine harrow modular weeding frame.

3.3. History and origins

Spring tine weeders evolved from tillage / cultivation zig-zag / chain harrows. In the pre-herbicide era / pre-1950s, tillage harrows were widely used for weed management in cereals, particularly a final pass in autumn cereals. However while effectively controlling weeds, they often caused considerable harm to the crop, i.e., they were not very selective (section 2.9). The exact progression from zig-zag harrows is not well documented, or at least is lost in obscure publications. One such publication is Rademacher (1940) who reported on a "jointed harrow for weed control made by R. Sack in Germany" which appears to be the first step in the evolution from tillage harrows to spring tine weeders by making the tines longer and thinner (Figure 4).

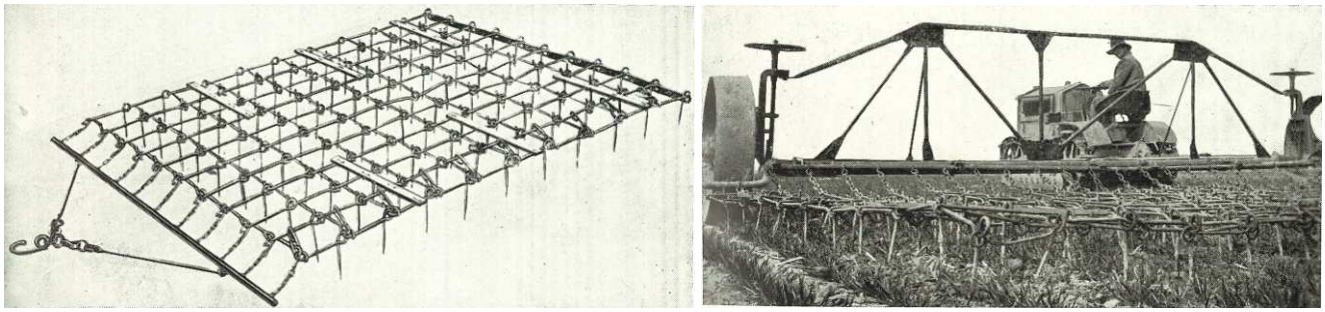


Figure 4. Left: "Jointed harrow for weed control, made by R. Sack, Leipzig. Photograph by Sack." Right: "Sack's weed harrow, wide pattern, drawn by a tractor. The great length of the tines and the adaptability of the harrow to surface inequalities are seen. Photograph by Sack." From (Rademacher, 1940. p. 88).

At the end of the 1940s Ferguson (as in Massey Ferguson) started production of the "Ferguson weeder" (Figure 4) which has clearly departed from the zig-zag / chain harrow design with much longer sprung tines mounted on a frame thus being half-way between tillage harrows and modern spring tine weeders.



Figure 5. The Ferguson weeder. Image credit www.fergusonclub.com/weeder.

Then in 1952 Thomas Hatzenbichler www.hatzenbichler.com in Austria developed the "Comb harrow" which is the first iteration of modern spring tine weeders including long thin sprung tines mounted on a frame, and the ability to adjust tine angle (Figure 6).



Figure 6. "Das Original Hatzenbichler Comb harrow". Photo credit Hatzenbichler Agro-Technik www.hatzenbichler.com.

All modern spring tine weeders are considered to be descendents of the Hatzenbichler “comb harrow” (Figure 7).



Figure 7. A range of spring tine weeders. Photo credits: bottom left, Chris Smith; bottom right, Treffler www.treffler.net.

3.4. Target weed and crop plant sizes

As discussed in section 2.4 it is weed size, **not** crop growth stage, that determines when to weed for mechanical weeding. The optimum weed size for all mechanical weeding is cotyledon stage. However, spring tine weeders are also able to control larger weeds, depending on variables such as the crop and how resistant it is to weeding, the morphology of the weeds, e.g., fibrous rooted grasses (monocots) vs. tap rooted broadleafs (dicots), soil conditions, etc. It is thus impossible to give hard and fast rules as to the largest weeds that can be controlled. A rough rule of thumb is that at four true leaves, pairs for broadleafs, then you have most likely run out of road.

The larger the weeds, the more important uprooting is to control them compared with severing and burial (section 2.3). Tine weeders are unlikely to sever larger weeds, especially grasses, or bury them, hence why uprooting is key. Setting the tine-soil angle so the tines are pointing forward, increasing downpressure and going slower is a good starting point for uprooting larger weeds.

Crop plants, particularly broadleafs (dicots), are considered to be quite to highly susceptible to spring tine weeding between shoot emergence from the seed (pre-em) and two to three true leaves (post-em) (Endres *et al.*, 1999; Cloutier & Leblanc, 2011; Einböck, 2023). However, for post-em weeding a number of experiments used moderate to quite aggressive weeding, including at higher speeds and using multiple passes as a means of achieving greater crop soil cover (CSC, section 2.9.1). When crops are small it is likely to be easier to cover them with soil (i.e., a larger CSC) and thus cause significant crop damage. In comparison, if tine-soil angles are set around 90° to the soil surface, downpressure set at lower levels to keep tine depth well above the crop seed, and speed kept slow, e.g., less than 4 kph / 2.5 mph, crops at early growth stages may well be able to be spring tine weeded as soil throw, and thus CSC will be minimised. This is also discussed in section 2.9.3. Doing on farm trials

(section 2.10) is critical to confirm this. Otherwise avoid using spring tine weeders late pre-em and early post-em.

Once crops are past the early post-em stage, i.e., established, they are increasingly tolerant of spring tine weeding. Key is the concept of crop soil cover (CSC, section 2.9) whereby too much soil on the crop, while not killing the crop plants outright, is likely to reduce yield.

When crop plants start to become taller than 10 cm / 4" research indicates that they may survive weeding looking pretty intact, but, it may be causing yield reductions (section 2.15).

3.5. How it works (mode of action) and how to use one

Spring tine weeders work by dragging their thin steel tines through the soil surface 1-5 cm / ¼-2" deep stirring and mixing the soil as well as throwing it around. They thus kill weeds through uprooting, severing and burial (section 2.3) with the first two contributing to most of the weed kill but the latter can also be significant especially when more soil is thrown around with faster speeds and deeper tine penetration into the soil.

In common with the rotary tine weeder, the horizontal movement of the mostly vertical tines means that they inevitably impact crop plants, knocking them over, potentially flattening them, especially cereals and covering them with soil, potentially large amounts of soil (Figure 8). This contrasts with the rotary hoe which has very limited horizontal movement through the soil, rather movement is almost entirely vertical (Figure 31). This knocking over of crop plants and especially crop soil cover (CSC, section 2.9) is considered to be the key mechanism by which tine weeders negatively impact crop plants in the absence of weeds, including reducing harvest yield. Accordingly adjusting tine weeders to minimise crop knockdown and CSC while still killing sufficient weeds is key to the art of tine weeding.

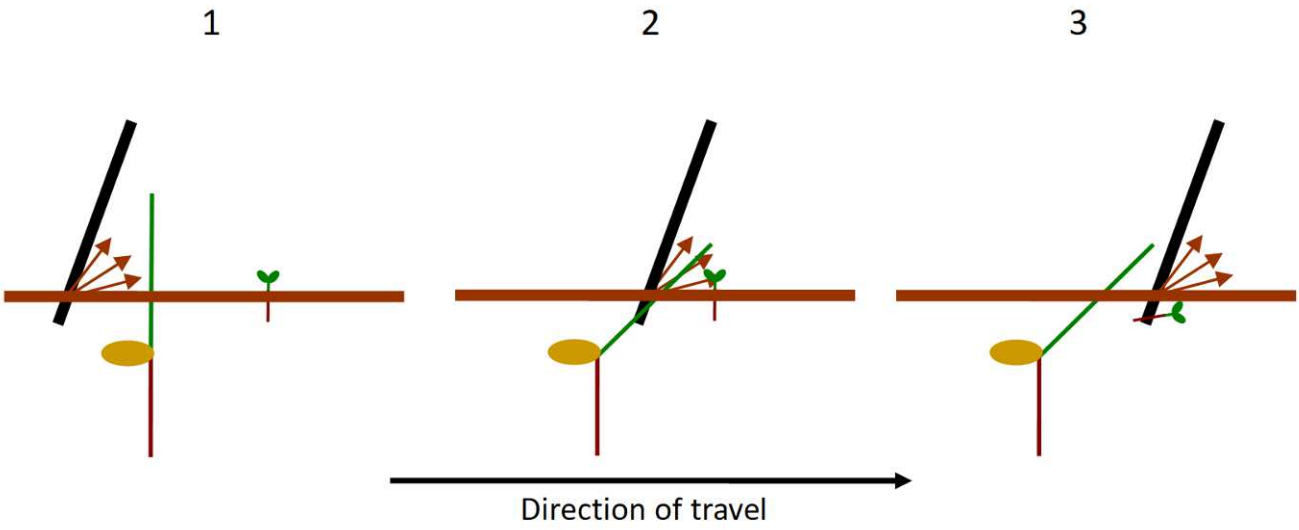


Figure 8. Spring tine weeder mode of action. Nearly vertical tine (black line) rakes through the soil surface shallower than the crop seed depth (wheat) but deeper than weedling depth (No. 1). The tine impacts crop shoot bending it and partly covering it with soil (No. 2). The tine digs up and buries weeds by throwing soil in front and to the sides of the tine. (No.3). N.B. compared to the rotary hoe where the spoon is stationary relative to the crop (Figure 31) for tine weeders the tine is moving relative to the crop.

There are three adjustments that can be made on spring tine weeders:

- Tine-soil angle - measured as the angle the tine tip makes with the soil surface.
- Downpressure.
- Forward speed.

Increasing tine-soil angle forwards, downpressure and forward speed all increases weeding aggressiveness. All three also interact, for example tine-soil angle can be increased to increase aggressiveness but with downpressure decreased so the tines don't dig into the soil so much. The interactions are thus both synergistic / additional, and antagonistic / cancel out to a degree. Thus there is a enough rope to get into trouble with.

Additional details on the design and use of 1st and 2nd generation spring tine weeders is provided in section 3.18.

3.6. Tine angle

In this report where the angle of the tine tip to the soil surface is being specifically referred to the term 'tine-soil' angle is used. Where more general statements about the angle of the tines is made the simpler term 'tine angle' is used.

Exactly the same as for tillage / cultivation equipment, if a tine tip points forwards it will dig into the soil and pull itself downwards. Backward pointing tines push down and compress soil while pushing themselves up and out of the soil. So, think about tine-soil angle and downpressure exactly the same as for tillage / cultivation tines as they are exactly the same. Figure 10 shows the five tine angle positions on a 1st generation (see below) Einböck spring tine weeder.

According to Einböck (Einböck, 2023, p100) out of the five tine angles in Figure 10 the highest position / smallest tine-soil angle is principally for transport and the lowest position / largest tine-soil angle is for combing climbing weeds out of cereals. That leaves the three middle tine angles for soil engaging weeding. Of those three settings the angle of the tine tip to the soil / ground are 80° (pointing slightly backwards), 90° (vertical) and 100° (pointing slightly forwards). When the tines are in their working position in the soil, and particularly with increasing downpressure, they will point further backwards i.e., the angles will decrease.

3.6.1. Going backwards

The main way spring tine weeders are damaged is driving backwards with the tines down and bending them. Always keep an eye on how close the tines are to the ground, especially around headlands where vegetation can catch the tines.

3.6.2. Tine bend angle

Tines for weeding are bent near the end at angles between 90° and 160° with around 135° being the most common on modern 1st generation weeders (Figure 9). (Tines for pasture care are straight (0° bend), so they don't pick up thatch, and are thicker and stiffer).



Figure 9. A range of spring tine angles from ~160° (left), the most common ~135° (middle) to now uncommon ~90° (right).



Figure 10. Five tine angles on a 1st generation Einböck spring tine weeder (modified for research plot use) from lowest angle top left to highest angle at the bottom left.

There are two key aspects to tine angle:

- Smaller tine bend angles, i.e., closer to 90° are more likely to pickup and accumulate residue as they form a hook shape.
- Tine bend angle interacts with the angle of the tine shaft to determine the angle that the tip of the tine enters the soil.

Figure 11 shows the effect of tine bend angles on the angle of the tine leg to achieve three tine-soil entry angles of 45° forward, 90° (vertical) and 45° backwards. The 45° forward and backward angles

are deliberately extreme and unlikely to be achieved in real-world use, but they are used to more clearly illustrate the effect of tine bend angle on achievable soil entry angles.

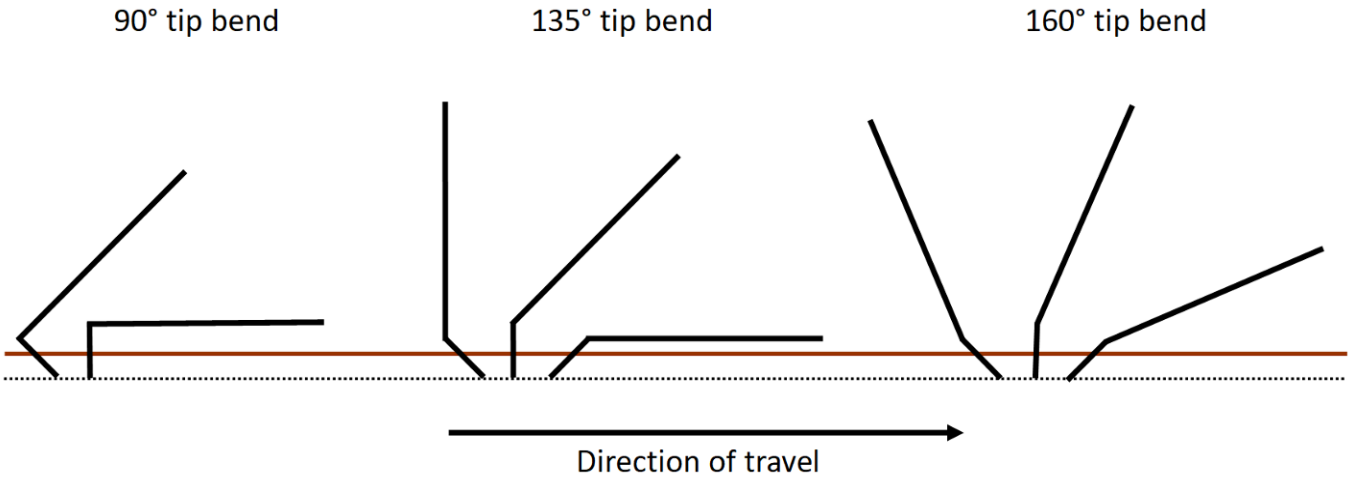


Figure 11. Effect of tine tip bend angle of 90°, 135° and 160° on the position of the tine leg at three tine-soil entry angles of 45° forward, 90° (vertical) and 45° backwards.

The 90° tine tip bend in Figure 11 easily achieves a high forward facing tine-soil angle that will aggressively dig into the soil. However, it would be impossible to even achieve a 90° (vertical) tine-soil angle as the tine leg would need to be horizontal to the soil which is unfeasible as the weeding frame would have to be on the ground. A backward pointing tine-soil angle needed for clearing residue is completely unattainable.

The 135° tip bend angle in Figure 11 can achieve both forward and rear tine-soil angles with viable tine leg angles (though clearly not as far as 45° backwards angle).

The 160° tip bend angle in Figure 11 easily achieves a backwards tine-soil angle that will effectively clear residue. However, to have a forward tine-soil angle requires the tine leg to be pointing forward which is mechanically impossible - the tine leg will bend or break.

Therefore, a tine bend angle of around 135° is going to give the widest range of usable tine-soil angles both forward and backward facing giving more and less aggressive weeding action as well as residue clearing as discussed in section 3.6 above.

It appears that early tine weeders, e.g., pre-1990s, had smaller tine bend angles often around 90° and that tine bend angle has increased over the years settling in around 135°. This may have been in response to smaller tine bend angles clogging with residue and/or being too aggressive. However, it appears that larger tine bend angles 110°-120° (i.e., nearly back to 90°) appear to be more common on 2nd generation weeders (see section 3.18) which impacts on them not being able to achieve the backward tine-soil angles required to minimise residue clogging as per Figure 11.

Some manufacturers offer a range of tine bend angles, as well as lengths and diameters for different crop and soil conditions. While it is possible to have two or more sets of tines for an individual weeder that can be swapped out for different jobs, for many weeders changing tines requires many hours work so it is unlikely to be practical or economic.

3.7. Downpressure

Downpressure is regulated on 1st generation spring tine weeders (section 3.18) principally by changing the height of the frame from the ground, typically via the depth wheels. As the frame is lowered the tines bend more creating more downpressure.

However, when the tine-soil angle is decreased by lowering the tines, as in Figure 10, the height of the tine tips lowers relative to both the frame and depth wheels and thus the soil, which also increases downpressure. Thus where tine-soil angle is decreased by lowering the tines but downpressure needs to be kept the same, then the frame height from the soil will also need adjusting, i.e., via lowering the depth wheels / lifting the frame. And vice versa, if the tines are lifted the depth wheels need to be lifted the same amount to keep downpressure the same, or even to keep the tines in the ground.

On 2nd generation machines (section 3.18.2) downpressure is regulated through the independent downpressure control system, which is adjusted manually, pneumatically or hydraulically. This achieves the same downpressure independent of tine angle, height of the frame above the soil, and over any unevenness of the soil surface, including weeding on ridges.

Determining the amount of downpressure on 1st generation weeders can be done in three main ways. First, simply looking to see how much the soil is being disturbed as the weeder is working and when inspecting results. Simple but not particularly precise. When the weeder is in the operating position and the tines are on the ground, pull on a few tines to see how much force is required to lift them off the ground. While this is somewhat more informative its still subjective. The third more objective approach is to use some hand / suitcase scales (Figure 12) to measure how much force is required by hooking them over the bend in the end of tine and seeing how much force is required to just lift them off the ground.



Figure 12. Digital hand / suitcase scales.

The best types are digital with a maximum hold function, as reading them at ground level can be fiddly. They also need to have a minimum resolution of around 50 g / 2 oz and have a maximum reading of at least 5 kg / 10 lb or best 10 kg / 20 lb. This directly relates to the independent downpressure of 2nd generation spring tine weeders that exert downpressures between 100 g / 3 oz to 6 kg / 13 lb per tine. The downpressure force is measured in this same way. The same approach is also used to check downpressure is constant across the full swing of the tine on 2nd generation weeders.

Using hand scales can be particularly useful when learning how to use spring tine weeders to get a better feel for the results of varying downpressure.

3.8. Forward speed

Speed can be both your friend and enemy with spring tine weeders. Key is that increasing speed increases the amount of soil throw and thus crop soil cover (CSC, section 2.9.1), often considerably (Figure 13).

- Slow speeds are generally between 2 to 4 kph / 1 to 2 mph.
- Medium speeds are about 4 to 6 kph / 2 to 4 mph.
- Higher speeds are around 6 kph / 4 mph and above.
- Maximum speeds typically are up to 20 kph / 12 mph, though faster speeds are possible in the right conditions.



Figure 13. The amount of soil disturbance at 4 kph vs. 8 kph / 2.5 mph vs. 5 mph. Image credit Einböck www.youtube.com/shorts/dBVglrYwgos.

When crop plants are small, and prone to being bent over, even flattened by the horizontal weeding action of the tines and buried by soil, higher speeds giving greater soil throw (Figure 13) will result in higher CSC and increasing negative impact on the crop, including harvest yield. Thus on small crop plants, slower is often better to minimise crop flattening and excessive CSC, even at the cost of lower work rates and weed control. This is backed up research which found that selectivity (section 2.9) decreases with increasing speed, at least in cereal crops. Thus, as discussed in section 3.4 and illustrated in Figure 13 at small crop plant sizes keeping speed low to minimise soil throw and CSC is important to minimise crop harm.

As the crop gets bigger / taller and more resistant to bending and CSC and also better able to recover from weeding, higher speeds with greater soil throw will kill more weeds and faster work rates is the way to go. Once again, on-farm trials on a crop-by-crop basis will be required to work out optimum speeds.

3.8.1. Putting it together - combining tine angle, downpressure and speed

With the three interacting adjustments of tine angle, downpressure and forward speed, combined with all the variables of crop, soil conditions, weed type and sizes, etc., there is no simple recipe for how to use a spring tine weeder. As said many times already, trial and error (section 2.7), or just playing around on some land without crop, is the best way to start.

As there is quite a distance front to back on a spring tine weeder it is important to have the weeder level so that the front and back tines are at the same depth in the soil / same downpressure and therefore doing the same intensity of weeding. While the frames may appear level, and tine sat the same depth, downpressure can still vary considerably so measuring downpressure using hand scales is the most accurate. Weeders with front and back depth wheels make this a lot easier.

Perhaps obviously, the place to start is the middle to lower end of each adjustments range, or at least avoid starting at the most intensive settings unless there is good reason to do so, e.g., a really tough crop with lots of weeds. Best to start on softer settings and ramp them up until crop damage starts, including excessive crop soil cover (CSC, section 2.9.1) rather than starting on aggressive settings and dialling back until the crop stops being shredded!

It is essential to get off the tractor and down on your hands and knees to see what is really happing at ground level, including digging into the soil to find the tine tips and crop seed plus to determine what it is doing to the weeds. This applies to all weeders.

First thing is to check the status of the crop:

- Are there (m)any crop plants pulled out?
- Are the remainder still well anchored / rooted?
- Are there many leaves that have been stripped off or damaged?
- What is the crop soil cover (CSC) i.e., how much have they been buried / covered with soil?

Then check the status of the weeds:

- Are there (m)any weeds that are still sufficiently rooted that they could survive?
- Are they attached to soil crumbs that could allow them to re-root?
- How many are getting buried?

Next check what the weeder is doing. When stopping the tractor leave the weeder in the operating position and use the breaks to catch any rollback as this will result in the tines pushing deeper into the soil:

- Are the frames level with the ground / front and back tines working at the same depth?
- What is the downpressure on the tines front to back (use a digital hand scale)?
- What is the tine-soil angle: pointing forwards / digging in, or backwards and pushing up?
- What depth are the tines reaching?
- Is the crop seed depth greater than the tine depth - with a safety margin - particularly for pre-em weeding?
- Is there any soil surface that is not disturbed by the tines or having soil thrown over it?

Based on these questions and analysis make adjustments and try again. As to what to adjust experience from tillage / cultivation equipment is a useful starting point. Adjustments include:

- If the tines are too deep drop the depth wheels / raise the frame height or on 2nd generation reduce downpressure.
- If the crop is getting pulled out or covered with too much soil, decrease working depth and/or slow down and/or reduce tine-soil angle (point them backwards more).
- With bigger weeds, increasing tine-soil angle, and downpressure while reducing speed can be effective.
- With smaller crop plants, slowing down, using a neutral 90° tine-soil angle, medium depth but increasing downpressure should reduce soil throw and thus crop soil cover (CSC) while still taking out weeds.
- On well established crops, increasing speed and having a smaller tine-soil angle (pointing forwards more) will increase soil throw so increasing CSC which will also bury more weeds, and increase work rates.

Nevertheless, it is impossible to write an exhaustive list, so just trying different settings based on your tillage / cultivation experience and expertise, coupled with watching videos and just trying things out is how best to learn what works and what does not.

3.8.1.1. An example of weeding a delicate crop in challenging conditions

While a lot of damage can be done to young crops with spring tine weeders, when used correctly it is impressive how many weeds they can control in even the most delicate crops in really challenging conditions. For example, Figure 14 shows a crop of transplanted carrot stecklings for seed production. The field had been ploughed and tilled / cultivated. Finger sized stecklings with a handful of leaves were manually transplanted into furrows made with a vertical rigid tine and soil kicked back around them. They are on a 60 cm / 24" interrow spacing and 30 cm / 12" intrarow spacing . The soil is clearly very stony and a pure silt texture. This represents a really challenging situation for spring tine weeding, or pretty much any mechanical weeding! The crop is very poorly anchored / rooted but

has feathery leaves that can easily catch on tines, and it is very low density so any plant losses have to be replaced. The soil is very stony and the weed pressure is insane.

The crop was weeded using a 13 m / 42' wide 1st generation spring tine weeder at vertical to backwards tine-soil angle, higher downpressure and about 2 kph / 1 mph, with two passes in opposite directions on the same bout, when the weeds were at cotyledon stage and around two weeks since the crop was transplanted. Vertical tine-soil angle combined with higher downpressure meant the tines were pushing down on the soil more than pulling it up, so less likely to pull carrots out. The high downpressure also meant the tines were deep enough in the soil to move it around and thus kill weeds. The slow speed gave the carrot leaves time to move around the tine rather than getting caught and pulled out. Weeding twice in opposite directions minimised the amount of missed soil surface and hit the already damaged weeds again.



Figure 14. The edge of a carrot seed crop, using manually transplanted steckling, that have been weeded with a spring tine weeder, showing the difference in weed populations with the tilled / cultivated but unweeded ground on the left and weeded crop area on the right. The plough furrow is visible in top left of photo.

The left side of the photo in Figure 14 shows the unweeded area, where the soil had be tilled / cultivated but the tine weeder did not reach clearly showing the very high weed pressure. The right side of the photo shows the weeded area and carrot stecklings. Clearly the amount of weeds controlled is exceptional. Also clearly not every weed was controlled, there are a small number visible in the weeded area, but the crop was then interrow-hoed, so all interrow weeds were then fully controlled. Less than one in some 500 crop plants were pulled up so replanting was not onerous. Without a doubt, this is excellent weed control in the most challenging conditions.

3.9. Working conditions

3.9.1. Soil

Building on the comments in section 2.7 the ability of spring tine weeders to penetrate hard soil is limited, even for 2nd generation weeders which can create downpressures of up to 6 kg / 13 lb per tine. The length and thin diameter of the tine means the whole tine will bend if the soil is too hard. Spring tine weeders will therefore only work effectively in tilled / cultivated soils.

The surface tilth also needs to be reasonably fine, e.g., soil crumbs / aggregates need to be less than 1.5 cm / ½" otherwise the tines cannot move the soil around enough and weedlings can be protected by the soil lumps. With bigger pieces of soil there is also an increasing risk that when they are thrown around they will damage crop plants.

In terms of moisture content, dryer is better, but moisture levels can be quite high as long as the soil can still crumble and move around the tines as they pass. Too wet is where the plastic soil state is approached and soil becomes 'cheesy' with soil crumbs no longer moving around the tines but deforming and squishing as the tine hits them. Having said that, weeds will still be killed, so if the weeding program is between a rock and a hard place, even weeding in such poor conditions may be better than not weeding, as long as the crop is not damaged too much. Clearly a mess will be made, especially in sticky silty soils, as well as some smearing.

3.9.2. Stones and clods

As stonyness and cloddiness increases, weeding efficacy decreases, as the stones and clods push the tines out of the soil. Thus there is a considerable difference between a soil with some small stones / gravel, and a moderately stony soil that has large, e.g., fist sized stones. To an extent small and gravel sized stones are more like large soil crumbs, so the spring tine weeder can move them around. Large stones are simply to heavy for the tines to move so they will skip over them, and fail to impact weeds growing around them.

With stony and cloddy soils more aggressive settings, such as increased downpressure, will be required to keep the tines in the ground, but at the risk of increased crop damage. Thus there is a point where weeding effectiveness decreases, and/or crop harm increases that spring tine weeders become ineffective due to too many stones and/or clods.

While stony soils can limit the efficacy of spring tine weeders, they are very unlikely to harm the weeder, except through increased tine wear. Indeed you could drag a tine weeder along a road, either tarmac or gravel and it would be fine!

3.9.3. Residue

While spring tine weeders are akin to a giant spring rake, they can cope with moderate amounts of residue. Shorter stiff residue, e.g., chopped cereal straw will flow through the tines a lot easier than longer bendy residue such as pea vine. Key is using a backward tine-soil angle so the residue has a chance to slip under the tine as it builds up. Lower downpressure to achieve the same, and slower working speeds allow residue to better flow around the tines. However, spring tine weeders will never cope with large amounts of residue, they will simply block up.

3.9.4. Weather

With a large proportion of the weeds not fully killed by the weeding action, e.g., they are only severed through the roots not the hypocotyl or just uprooted, they need to desiccate to die. Thus clearly hotter, windier and better drying weather will speed up weed death while cool, calm and overcast conditions will take longer to kill the weeds. If there is sufficient soil moisture there is a greater chance of weeds re-rooting and regrowing. At the same time a reasonable number of weeds are killed by burial which is not dependent on weather conditions for an effective kill, so even though the proportion killed by severing and uprooting are lower in cooler wetter conditions, overall a considerable proportion of weeds will be killed. Consequently while the number of weeds that survive weeding in poor weather is greater than hot weather, more weeds will survive if weeding is postponed until better weather arrives and the weeds have grown bigger and harder to kill. Accordingly, it is better to weed when the weeds are the optimum size, i.e., cotyledon, than wait for better weather and let the weeds get too big.

3.10. Tine horizontal spacing

The horizontal spacing between adjacent tines varies from about 20 mm / ¾" up to nearly 40 mm 1½". Typically narrower spacings are associated with thinner tines and wider spacing with thicker tines. This may not sound like a large difference, especially compared with cultivation tines, but, when weeding delicate crops at slower speeds, and lower downpressure having as small a gap as possible between adjacent tines is often key to achieving good weed control due to more tines directly impacting weeds and relying less on soil throw and burial. Consequently, for less robust crops, particularly vegetables, having a smaller gap between adjacent tines is likely to be valuable. While for more robust arable / row crops fewer, thicker tines that are used at higher speeds creating more soil throw may give better results. However, there is no independent testing of this.

3.11. Tine tip wear and carbide tips

Like all soil engaging components, tine tips wear with use, and once they have worn around half the original tip length their weeding efficacy will decrease to the point that they should be replaced. Typically the whole tine is replaced as the tines are spring or at least tempered steel so welding new tips on will be difficult if not impractical and uneconomic. Comparing the price of replacement tines among manufactures at the time of purchase can be an informative exercise!

An increasing number of manufactures have tungsten carbide tipped tines as optional extras or as standard. Tungsten carbide is more than an order of magnitude, even >100x, harder than steel (Mohs hardness of 8.5–9.5 for tungsten carbide vs. 6.0 for spring steel) so will wear considerably slower than steel. Particularly on more abrasive and stony soils and/or where large areas are being weeded, these may well be an economical option, despite the higher purchase price, especially when considering the labour and materials cost of replacing a set of tines. The value of carbide tips can be evaluated by swapping some carbide for standard tines when new, spread across the weeder, and comparing wear rates over time. Having carbide tipped tines only behind the tractor wheels is another option where the more compacted soil results in greater tine wear.

3.12. Ridge weeding

Spring tine weeders can be used to weed crops on ridges such as potatoes. For 1st generation weeders (section 3.18.1) the limitation is that the downpressure is largely determined by the tine height / position. Thus, tines on the top of ridges will have high, even very high downpressure and thus weed very aggressively, exactly where the crop is, so potentially causing significant crop damage. While the tines in the bottom of the furrows will have the least downpressure where they need it the most to dig into the harder soil, especially in wheelings. The tines on the top of ridges can be tied up to make an incontiguous weeder (section 3.16) to avoid crop damage, at the expense of no weeding occurring among the crop plants. The tines on the sides of the ridges will still pull the ridge down, which may or may not be what is required. Alternatively the weeder can be setup so it only is weeding the top of the ridges where the crop is, and different machinery is used to weed the ridge sides and bottoms.

2nd generation spring tine weeders (section 3.18.2) with constant downpressure independent of tine height are therefore much better suited to weeding ridges. Indeed this ability is one of the key selling points for 2nd generation machines.

3.13. Crop plant clearance

Spring tine weeders have the highest crop clearance of all three weeders due to the long length of the tines. They can potentially get through considerably taller crops than rotary tine weeders and rotary hoes. The key caveat is the indications from research that using contiguous weeders at larger crop

growth stages may be impacting yield (section 2.16). The next caveat is if the crops' foliage starts to catch on the tines, pulling plants out and wrapping round the tines and blocking them. Fast speed is the enemy of working in tall crops, so going slow and giving the crop foliage time to slide around the tines rather than grabbing hold of them is key. Couple that with angling the tines forward and using higher downpressures to maximise soil disturbance to achieve a good weed kill at the slower speeds.

3.14. Raking out weeds

As briefly noted in section 2.5 contiguous weeders mostly wont kill established weeds. However, there are a few situations where spring tine weeders can play a useful part in managing established weeds, including helping reduce weed seed rain.

The ability to rake residue up can be advantageous for stoloniferous and rhizomatous weeds by pulling them up to the soil surface or to the field edges, i.e., using the spring tine weeder like a giant spring rake. Where the stems or roots are quite short, e.g., less than 15 cm / 6" such that they can flow through the tines, then setting the tine-soil angle forward so they dig into the soil, ramping up the downpressure and going quite slowly e.g., 3 kph / 2 mph should result in the tines digging up the stolons or rhizomes and leaving them on the soil surface where they can be left to desiccate or eaten by livestock such as sheep (which often relish them as they are tasty and nutritious because as perennating organs they have higher nutrient and energy levels).

Where the stolons or rhizomes are longer they are more likely to wrap around the tines and collect on them. Using the same settings the pieces can then be pulled out of the field to the headlands were they can be dealt with or collected and removed from the field. Clearly there are limits to this with larger fields and large infestations of weeds where the amount of weed means it is impractical. A potential option for such situations is to pile the weeds up in windrows across the filed, pulling them in from both sides, and then managing the windrows by grazing, baling, or desiccating and burning, for example.

Another potential use is to rake climbing weeds, such as cleavers (*Galium aparine*) and field bindweed (*Convolvulus arvensis*), out of cereal crops as they mature (Einböck, 2023, p100). This requires the tines to be set as far forward as possible, keeping them off the ground, then slowly and carefully driving through the crop so that they catch on the weeds' climbing stems and pull them off the crop. Again there are clear limitations to this approach. It is only likely to work on the upright, unbranched stems of cereals and not broadleaf (dicot) crops. Where there are a lot of climbing weeds the tines will quickly clog with the weeds foliage and start flattening the crop, such that potentially many trips down the same tramlines are required. Getting the weeds off the tines can be challenging. For 1st generation weeders getting some speed up and hitting the breaks hard can dislodge the weeds. 2nd generation sprig tine weeders (section 3.18.2) where the tines can be remotely retracted thus dumping the weeds off the tines may work. However, many 2nd generation weeders lack independent tine angle control so they may not be so effective at pulling the climbing weeds out in the first place. Thus, this is quite a niche approach, but could be a get-out-of-jail-card in some situations, particularly to minimise weed seed rain.

3.15. Big weeders - weight and wheels and working on slopes

As the width / size of weeders has continued to increase, there are diverging views among manufacturers and users about machine weight and depth wheels. Some are going the minimalist direction and trying to have as light a machine as possible. Others have gone full monty with deliberately greater weight. My personal observations are that while trying to have lighter machines has the benefit of not needing such a big a tractor to lift the weeder on the three point linkage, lighter machines, especially those with only central depth wheels suffer from 'tip bounce' where the outer wings of the weeder bounce or 'flap' as the weeder travels down the field. While the independent

downpressure systems of 2nd generation weeders (see section 3.18) can (partly) compensate for this, that is not true of 1st generation weeders. For 2nd generation weeders that can produce up to 6 kg / 11 lb of downpressure across hundreds of tines the overall machine weight needs to be considerably greater than the combined downpressure on all the tines otherwise the weeder will end up 'floating' on the tines rather than sitting solidly on the depth wheels. I therefore believe that heavier machines, and having depth wheels as close to the ends of the weeder as possible, will give better weeding precision, potentially put less stress on the frame, and especially folding hinge points, due to better support from the wheels. As an illustration, the research plot weeder in Figure 10 with a working width of 1.5 m / 5' has 180 kg / 400 lb of additional weight added to it to ensure it's stability! That would be equivalent to adding 1.2 tonnes / tons of ballast weight to a 10 m / 30' tine weeder!

In a similar fashion some weeders, often the lighter ones, have taken a minimalist approach to depth wheels. Having a pair of depth wheels on the front of the machine following in the tractor wheel tracks is pretty much obligatory. Some then add one more pair of wheels on the front of the folding sections. Others have multiple wheels, both front and back across the whole width of the weeder. Ideally these are placed in wheel tracks or between crop rows, with the outside ones positioned as close to the outside edge as possible to minimise tip bounce. The same as for weight, I favour larger numbers of depth wheels, both front and back, to ensure stability and also carry the weight of heavier machines, and having wheels as close to the outside edges of the weeder to minimise tip bounce.

Having a greater number of depth wheels, both front and back is also advantageous when working on slopes by providing greater resistance to the weeder crabbing down slope. More depth wheels will also help on undulating ground by allowing the individual sections to better follow ground contour.

3.16. Turing a contiguous spring tine weeder into an incontiguous weeder

For more widely spaced rows, e.g., greater than 30 cm / 12", typical of N. American row crops, there is a technique that allows crops to be weeded with spring tine weeders at very early growth stages where they would normally be harmed. This involves simply tying up the tines over the crop rows, e.g., using baler twine, cable ties, etc.) so the crop rows are unweeded. This effectively turns a contiguous spring tine weeder into an incontiguous weeder!

Clearly the need for accurate weeder placement is essential, so the crop gaps in the weeder line up with the crop rows, the same for all incontiguous weeders. Due to the weeder being on the back of the tractor and the working length being quite long, some form of guidance system (e.g., RTK GPS auto steer) is essential unless very large crop gaps, e.g., at least 10 cm / 4" are used, otherwise the interrow tines are likely to hit the crop rows and rip crop plants out.

In addition, as the crop row is not being weeded the weeding intensity, i.e. downpressure, tine-soil angle and speed, can all be considerably increased, even maxed out, thus achieving much greater weed control in the interrow, providing extra value for the technique.

So, while it is a bit of a faff to tie up all the tines over the crop rows and then untie them again, the ability to get in and spring tine weed a crop at early growth stages could be the difference between good vs. poor weed management. So, particularly where incontiguous row-hoes are unavailable, the ability to make a spring tine weeder incontiguous can be a get-out-of-jail card.

Some 2nd generation spring tine weeders (see section 3.18.2.5 below) have systems where individual tines can be manually locked up while others can control the downpressure / position of individual tines, or banks of tines, so there is a lower weeding intensity in the intrarow (crop row) and more intense in the interrow. That this ability to have different levels of weeding in the interrow and intrarow has been built into some 2nd generation spring tine weeders reinforces the value of the technique.

3.17. Tine 'hooking'

One issue with a few spring tine weeder designs is adjacent tines 'hooking' over each other while in use. This is caused by a tine being pushed out of the ground and sideways at the same time so that it catches or hooks on the neighbouring tine Figure 15.



Figure 15. Example of a 'hooked' tine.

This means there is now an unweeded gap where the hooked tine is, and the tine carrying the hooked tine now has double, or even more, downpressure so it may start killing crop plants. There is no known research on the cause of tine hooking, but it is likely to be a problem where tines are more springy / flexible, are longer, have a larger tine tip angle and/or where adjacent tines on the same bar are closer to each other. It is easy to determine if hooking is likely to be an issue for a particular weeder design, simply try and hook a tine over the one next door. For many spring tine weeders the tines simply refuse to hook even when forced. If the tines hook easily, particularly across the full range of tine angles, then, it is at risk of hooking when in use. If so, it's probably best to look for a different machine.

3.18. Three 'generations' of spring tine weeders

Somewhat surprisingly for a machine so fundamentally simple, there are now two 'generations' of spring tine weeders with a third on the way. 'Generations' is my terminology.

1st generation spring tine weeders are entirely mechanical and mostly manually adjusted. The ability of the tine to flex is part of the tine, i.e., the tine is the spring. Adjustments are downpressure, tine angle and forward speed. These are also called 'traditional', 'classic' and similar names.

2nd generation spring tine weeders are defined by the downpressure on the tines being constant (or nearly constant) regardless of the vertical deflection / angle of the tine with downpressure being controlled by a mechanism separate from the tine i.e., the tine is no longer the spring. I describe this as 'independent downpressure'. 2nd generation spring tine weeders are also called / branded as 'precision' (the most common term), 'premium' and 'professional / pro'.

3rd generation spring tine weeders are based on computer vision systems analysing the amount of crop soil cover (CSC section 2.9.1) and adjusting the intensity of harrowing on the fly to ensure that the crop is not excessively harmed while maximising weed kill.

This section compares the three generations of spring tine weeders and also provides details on their construction and use, in addition to the more general information provided above.

3.18.1. 1St generation spring tine weeders

Most 1st generation spring tine weeders are built on a modular system consisting of a 'wishbone' which supports the 'weeding frame' on which the tines are mounted (Figures 3 & 16). The wishbones are attached to the toolbar by a horizontal axis pivot that allows them to turn side to side to follow ground contour (Figures 3 & 16).



Figure 16. Einböck spring tine weeder, modular wishbone and frame (left) larger weeder folded for transport (right). Pneumatic seeder distribution pipes and seed outlets can be seen on the left hand photo.

The weeding frames / modular units are typically 1.5 m / 5' wide with four to eight rows of spring tines (Figures 3 & 16). For larger width machines the wishbone units pivot to allow the toolbar to be hydraulically folded (Figure 16).

For spring tine weeders with modular wishbone and weeding frame designs (Figures 3 & 16) commonly have the ability for the weeding frames to 'float' or exert extra downpressure depending on the position of the wishbone ends. When in the floating position, e.g., the frame is pulled along by the front lifting chains, so only the weight of the weeding frame creates downpressure. By lengthening the top link the wishbone ends push down on the weeding frame increasing downpressure. The front of the weeding frame is still however being pulled by the lifting chains, there is no extra downpressure on the front of the weeding frame. Generally the aim is to use the weeding frame in the floating position and use tine angle and speed to regulate weeding intensity, but, if greater downpressure is required then this is how it is achieved.

Most weeders, particularly larger weeders have depth control wheels. At a minimum there is one pair on the front of the toolbar directly behind the tractor wheels. For wider machines additional depth control wheels are placed on the front of the toolbar, typically aiming to run along existing wheelings. Spring tine weeders designed for highly precise depth control have additional depth wheels placed behind the weeding frames (Figure 17).

Due to the potential for the rear wheels to push uprooted weeds back into the soil some manufacturers have additional tines behind the rear depth wheels to reloosen the soil. However, considering that the weeds in the wheelings will have been weeded by the tines, they are growing in the more compacted wheelings, and they will have been crushed by the depth wheels both front and back (and tractor wheels in tractor wheelings), it is considered unlikely that the rear wheels will increase weed survival through 'replanting', and thus after-wheel tines are unlikely to be achieving additional weed control. Conversely the extra tines could well cause even more crop harm for the same reasons - the crop plants have been weeded the same as the rest of the crop, driven over by both tractor and weeder, and then weeded again while trying to grow in the compacted wheeling soil.



Figure 17. Rear depth wheels on a 1st generation Einböck AEROSTAR-EXACT spring tine weeder. Photo credit www.einboeck.at

3.18.1.1. Adjustments

Tine angle is mostly manually adjusted on each frame by a lever - i.e., all the tines on the frame use the same tine angle and are adjusted together. On some machines, particularly larger ones, there is remote adjustment of the tine angle, e.g., by hydraulic ram attaching to the hand lever system. Typically remote adjustment can only set a single tine angle across the whole weeder, i.e., individual frames cannot have different tine angles.

Downpressure adjustment is achieved by varying the height of the frames from the ground by altering the depth wheel height. As changing tine angle, alters the distance between the tine tips and the frames (see Figure 10), this means changing tine angle will also change downpressure. To keep downpressure constant when changing tine angle the depth wheels (height of the frame from the ground) will also need to be adjusted.

Speed is obviously controlled by the tractor!

3.18.1.2. Tine attachment

There are a wide range of ways the tines are attached to the horizontal bars on the weeding frame as well as the type of bar, e.g., round vs. rectangular. This can result in significant differences in how well the tines are clamped to the bar without twisting and thus how well the height of the tine tips are kept equal as machines age and wear. Uneven tine tip heights will results in different downpressures and thus weeding depths, among the tines which can result in crop damage due to too much downpressure, and/or poor weeding performance due to insufficient downpressure on individual tines. Careful study of how the tines attach to the bars, along with looking at older machines that have done a good number of hours will indicate which designs are better than others. At least be aware that this is an issue for some weeder makes.

3.18.2. 2nd generation spring tine weeders

2nd generation spring tine weeders were pioneered in the early 2000s by Treffler www.treffler.net. Treffler used a coil spring and wire rope system with an attachment point on the tine such that the downpressure on the tine was independent of their height (Figure 18).



Figure 18. Treffler coil spring and wire rope downpressure system.

This means that regardless of the angle / height of the tine, the downpressure is constant, even in extreme cases such as potato ridges where the tine at the top of the ridge has the same downpressure as the tine at the bottom of the furrow. This compares with 1st generation weeders where as the tine is pushed upwards the downpressure increases, as the tine itself is the spring. For flat ground this not much of an issue but on more undulating ground and especially for ridge production systems it means that for 1st generation weeders the tines on the top of the ridge are pushed up, creating a lot of downpressure and weeding very aggressively, exactly where the crop is. While the tines at the bottom of the furrow may just be touching the ground where the most aggressive weeding is required, so the opposite of what is required for effective weeding.

For around a decade Treffler were the only company manufacturing 2nd generation spring tine weeders, but in the last ten or so years, an increasing number of companies have introduced 2nd generations weeders, indicating their value.

3.18.2.1. Independent downpressure mechanisms

There are a range of independent downpressure mechanisms among manufacturers. The most common is a system of coil springs attached to the tines via wire ropes or rods. On smaller machines, the spring tension may be adjusted manually, as in Figure 18 which uses a ratchet mechanism pulling the wires over a roller. While on larger machines it is typically remotely controlled from the tractor seat using the tractors' external hydraulics, either directly or a through a control terminal. Other approaches to controlling downpressure including direct hydraulic or pneumatic systems (Figure 19).



Figure 19. Independent downpressure mechanisms on 2nd generation spring tine weeders. Coil spring with hydraulic adjustment (left, photo credit Chris Smith), pneumatic (center, photo credit Chris Smith), direct hydraulic (right). Right photo shows single frame design, center photo shows original modular wishbone design.

With the advent of independent downpressure a number of manufactures have moved away from the modular wishbone design of 1st generation weeders (section 3.2) and instead they use a single frame, relying entirely on the independent downpressure to allow tines to follow ground contours (Figure 19). At the other end, a few manufactures have retained the modularity of 1st generation weeders and one has fully retained the wishbone and frame design of their 1st generation weeder and added independent downpressure at the individual tine level (Figure 19). The pros and cons of these different approaches are yet to be independently determined in any detail. However, the more complex systems retaining the modularity of 1st generation weeders are likely to allow more flexibility than single frame designs.

There is also variation among machine designs as to the ability to vary downpressure settings across the machine's width. At one end the downpressure is the same across the whole machine. At an intermediate level the folding sections can have different downpressure but not different downpressure within a section. At the other end, downpressure for every single tine can be individually controlled. This means that the tine pressure over the crop row and interrow can be different, soft on the crop row, hard on the interrow, turning a contiguous 2nd generation weeder into an incontiguous weeder (section 3.18.2.5).

3.18.2.2. Pros and cons of 2nd generation spring tine weeders

The ability to change downpressure and thus weeding intensity from the tractor seat while moving is perhaps as valuable, or even more valuable, as having constant downpressure regardless of tine height. This means that downpressure can be increased on the move where weeds are thicker, and reduced where they are lower, or the crop is weaker and could be damaged. As discussed in the section on 3rd generation spring tine weeders below, varying weeding intensity by changing downpressure can be really valuable in avoiding crop damage while maximising weed control.

In addition, with the increasing size of weeders, manually changing downpressure (and tine angle and depth wheels) becomes quite time consuming. Thus being able to adjust downpressure from the tractor seat represents a significant time saving.

The range of downpressure achievable by 2nd generation weeders is also considerably more than 1st generation machines. Depending on the weeder manufacturer, downpressure can be as low as 100 g / 3 oz to as high as 6 kg / 13 lb. That is a lot of pressure on a ~6 mm / ⅛" diameter tine! The downpressure is also typically infinitely variable between the minimum and maximum pressures, while on 1st generation weeders downpressure was mostly manually adjusted in fixed increments, with the additional complexity that changing tine angle also changed downpressure.

The obvious downside of 2nd generation weeders is the increased complexity means higher capital cost. Increased complexity also means that breakages of the downpressure system are more likely to put the whole machine out of action. This compares with 1st generation machines where failure / damage was mostly likely to be to individual or a few adjacent tines, which would have had a small impact, as the machine as a whole would still being usable, just with less effective weeding where the broken tine(s) are.

3.18.2.3. Controlling tine angles

For many 2nd generation spring tine weeders constant downpressure has come with the compromise of giving up tine angle control. The tines have a maximum forward working angle in relation to the frame, so to change tine-soil angle the height of the frame from the ground is changed (Figure 20). If a more forward pointing tine-soil angle is required the height of the frame is raised, and vice versa, the frame is lowered for a more backward angle (Figure 20). The downpressure system then automatically keeps downpressure the same for the different frame heights / tine-soil angles.

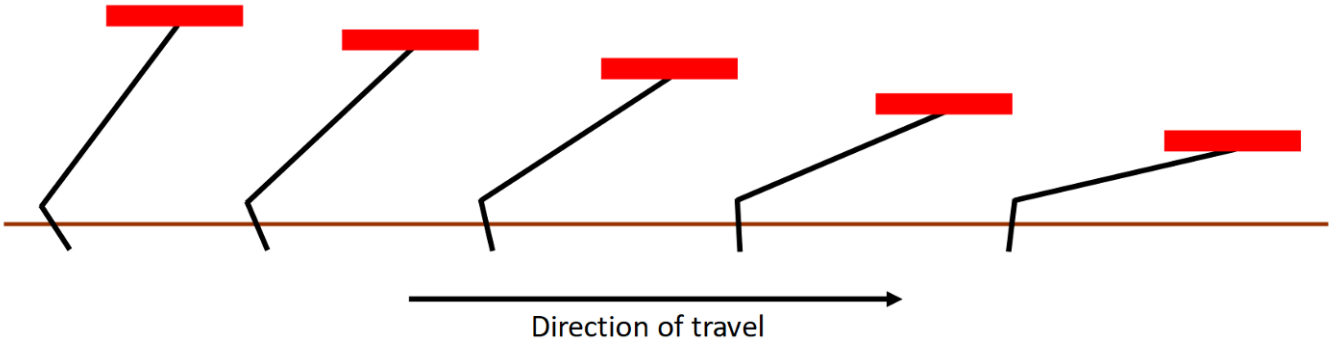


Figure 20. Effect of frame height (red rectangle) on tine-soil angle, based on a tine tip bend angle of 110°.

However, as can be seen in Figure 20 the range of tine - soil angles that can be achieved by changing frame height on 2nd generation weeders is often less than the direct tine angle control of 1st generation weeders as seen in Figure 10. As 2nd generation weeders have a tine bend angle of around 110° it means the tine tips are nearly always pointing forward, except for very low frame heights which may be impractical to use (Figure 20). So while the tine tips can be angled aggressively forward, it is difficult to impossible to have tine tips pointing backwards. On larger weeders with multiple depth wheels manually changing frame height via the depth wheels to change tine angle will be quite time consuming. That contrasts with tractor seat control of downpressure. Thus for many 2nd generation weeders, frame height and thus tine angle tend to be kept the same and weeding intensity is principally adjusted through downpressure and forward speed.

There are a small number of manufacturers who have kept independent tine angle control on 2nd generation weeders, which could prove to be quite valuable in some situations.

3.18.2.4. Tine sideways flex

Another change Treffler's 2nd generation spring tine weeder introduced is minimising the sideways flex of tines. For 1st generation weeders, with the tine being the spring, they inherently flexed both sideways and vertically, often considerably (e.g., see tine hooking section 3.17). Sometimes this sideways flex is useful. As the tine vibrates sideways it increases the width of its 'footprint' i.e., the horizontal area it weeds, thus increase the amount of soil directly impacted by the tines. It can also result in tines being forced away from the more compacted soil in crop rows due to the drill's press wheels and the presence of high crop plant populations in arable / row crops, which can help protect crop plants at early growth stages. However, as the crop grows and becomes more tolerant of weeding, having the tines pushed out of the crop row means it is not weeded as effectively. Tines can also end up following the same path as adjacent tines as they create small furrows in the soil, particularly in harder soil, so strips of soil end up unweeded. On ridges, such as potatoes, tines that can flex sideways can slip off the top of the ridge and slide down the side, so for weeding ridges minimising lateral movement is vital. So, whether having tines have some sideways flex or minimal sideways flex can be both good and bad depending on the situation. Most 2nd generation tine weeders minimise tine sideways movement, often because the tine hinge inherently limits sideways movement.

3.18.2.5. Incontiguous operation

A small number of manufacturers have implemented systems where banks / strips of tines (front to back) can have different downpressures. For crops on wider row spacings, e.g., greater than 30 cm / 12" it allows different weeding intensities in the intrarow (crop row) and the interrow. Other machines can manually or remotely fully lift individual tines off the ground entirely. These features therefore turn a contiguous spring tine weeder into an incontiguous weeder (also see section 3.16).

This means that no, or a (very) gentle weeding action is applied to the intrarows and a much more aggressive weeding action to the interrows. This is particularly valuable at early crop growth stages where the crop is more easily harmed by spring tine weeding, particularly broadleaf crops like soya. Having aggressive weeding in the interrow means also much better weed control in that area. As weeds that emerge with the crop are often responsible for the greatest yield losses, being able to have different weeding intensities in the intrarow and interrow and thus allow weeding to occur during and immediately after crop emergence is potentially exceptionally valuable. If row-hoes are not available, the value of having different weeding intensities in the intrarow and interrow is even greater. For cropping systems on wider rows, this ability could well be as, if not more, valuable than independent downpressure and/or tractor cab downpressure adjustment.

3.18.3. 3rd generation spring tine weeders

The 3rd generation of spring tine weeders are in the process of being commercialised (Roland Gerhards, pers. comm.). They are based on measuring crop soil cover CSC (section 2.9.1) with cameras mounted on the front and back of a spring tine weeder, using computers to calculate crop soil cover (CSC) in real-time and adjust the tine angle / weeding intensity on the move to maintain constant CSC within safe limits (Figure 21), (Rueda-Ayala *et al.*, 2013; Peteinatos *et al.*, 2018).



Figure 21. Computer vision system for continuously adjusting spring tine weeding intensity. Image (Spaeth *et al.*, 2021).

The next logical stage in this concept is to measure the weed density at the same time as CSC, rather than just excluding it from the analysis, and increase weeding intensity when there are more weeds and reducing it when there are less (Rueda-Ayala *et al.*, 2015; Spaeth *et al.*, 2020; Berge *et al.*, 2024). The logic is that where there are lots of weeds it is better to increase weeding intensity to better control the weeds at the expense of greater negative impacts on the crop, but where there are fewer weeds, reducing the intensity and thus reducing crop negative impacts further. It would also reduce draft and thus fuel use.

3rd generation spring tine weeders can therefore potentially take much of the guesswork out of setting up / adjusting spring tine weeders. You would be able to just drive into the field, tell the weeder's computer what the crop is and perhaps some other key parameters, like crop size, weed density, and then just drop and go, and the computer looks after the rest! This could be a huge boon, with significant time savings, superior weed control and minimising direct crop harm and yield reductions. Clearly at a cost as the cameras, computer system, etc., are all going to add to the price, possibly significantly.

These automatic adjustment systems are also well matched for integration into 2nd generation weeders that already have remote downpressure control systems, i.e., minimal retrofitting is required.

It is noted that a significant amount of the research on CSC has used speed, multiple passes and tine angles to control weeding intensity and CSC, while 2nd generation weeders only change downpressure to vary intensity and CSC. As the negative impact on the crop is directly related to CSC, i.e., the CSC itself is the harm, it is not a proxy measurement for other harms, e.g., uprooting, then the crop impact due to CSC from changing downpressure should have a similar impact to CSC from changing speed, number of passes, and other methods of changing weeding intensity. All the same, verification is required that changing downpressure has the same effect on CSC and crop yields as the other methods of changing weeding intensity.

I believe that automatic adjustment will also be increasingly important on larger weeders. The maximum width is now at 30 m / 100' such that crop and weed conditions across the weeder could vary considerably, e.g., a weed patch. Automated adjustment systems could then vary intensity independently for different sections of the weeder to take into account the crop and weed variability across the weeder's width. This would however require multiple camera pairs across the width of the machine, with an associated increased cost and computing power (Gerhards *et al.*, 2021).

Also with larger machines, adjustment becomes increasingly time consuming, getting off and walking around the back of the weeder, or even to the adjacent bout, to see what it is doing takes longer the wider the weeder is. Thus automatic adjusted is increasingly beneficial as weeder width increases.

It is therefore hoped that 3rd generation spring tine weeders will be commercially available soon. That the range of crops they can work on will be increased through more research on CSC and that weed density will also be included in the measurement and adjustment systems as well as CSC. The potential to dramatically improve the usability and efficacy of spring tine weeders through automated adjustment is thus believed to be significant.

4. Rotary tine weeder

4.1. Key points

- Rotary tine weeders (RTW) were invented around 2010 with only a handful of manufactures.
- Due to a more aggressive weeding action RTWs can kill weeds up to about six true leaves depending on soil, crop and weather conditions.
- RTWs consist of a series of wheels with round, pencil thick, steel spokes radiating from a hub.
    - The wheels are angled to travel direction so that they rake horizontally through the soil surface, diagonally to the crop row.
    - Due to the rotation the tine ends punch into the soil so can penetrate harder soil and caps / crusts.
    - The rotation also means tines are only temporally in soil contact such that they can 'clean' themselves of residues and other blocking materials as they exit the soil.
- Forward speed is a decisive determinant of crop foliage damage, especially larger plants, with higher speeds increasingly ripping foliage.
- Downpressure primarily controls the depth of weeding and the amount of soil disturbed, so higher downpressure will increase weeding efficacy.
- Most designs can change wheel angles, with angles closer to travel direction decreasing weeding aggressiveness and overlap, while angles more horizontal to travel will be more aggressive.
- RTWs are unsuited for incontiguous and ridge weeding
- RTWs can work in the widest range of soil conditions of the three weeders particularly harder and caped soils.
- While hot and dry weather is best, rotary tine weeders will still achieve considerable level of weed control even in cool and moist conditions.
- RTWs can cope with moderate levels of residues, more than spring tine weeders, less than rotary hoes, but may bury small crop plants under lines of residue.
- RTW can also cope with moderate levels of stones and soil clods.
- Safe RTW crop plant clearance is around 10 cm / 4" though as for all weeders, use in later crop stages may reduce yield.
- RTW have a potential niche in aggressive cleaning up of perennial herbaceous crop in spring, prior to breaking dormancy and new foliage being produced.

4.2. Rotary tine weeder design

The rotary tine weeder consists of a series of overlapping wheels consisting of round steel rods set in a central hub mounted on a sprung swing-arm. The wheels are offset to the direction of travel between 15° and 30° such they turn slower than forward speed causing them to rake through the soil surface (Figure 22).

4.3. History and origins

Rotary tine weeders are the newest of the contiguous weeders. While I have not been able to determine a definitive history they appear to have been invented by ANNABURGER Nutzfahrzeug GmbH (www.annaburger.de) around 2010 and called the 'ANNABURGER UniHacke' e.g., www.youtube.com/watch?v=ugzDisqG21Q&t=59s, www.youtube.com/watch?v=b3q3SBl4hBs, www.youtube.com/watch?v=jfl_X8chxVY and www.youtube.com/watch?v=c9oNy6iiwiI. This included using the weeder as an intrarow weeder on a row-hoe (Figure 22). While ANNABURGER built a number of machines it appears that the company stopped production after a relatively short period.



Figure 22. Various rotary tine weeders. Einböck (top left) photo credit www.einboeck.at, APV (top right) photo credit www.apv.at, ANNABURGER (bottom left) photo credit www.annaburger.de, Feelcrop (bottom right) photo credit www.feelcrop.com.

The idea was then picked up by Einböck (www.einboeck.at/en/products/crop-care/weeding-technology/aerostar-rotation/) around 2015 who improved the frame design, created modular sections with hydraulic downpressure control including applying for patents (Einböck pers. comm.). The Einböck 'AEROSTAR-ROTATION' was the only design of rotary tine weeder that was available for a number of years, until around the 2020s when a small number of manufacturers also started producing them. The newer manufactures have often added 'unique selling points' (USP) to their designs.

However, the general concept of using thin, vertical, moving tines for weed control, including rotary designs, for intrarow weed control is not new as shown in Figure 23. What was new was using the concept in a contiguous weeder.



Figure 23. A range of intrarow vertical moving wire weeders. Left photo credit Steketee.

4.4. Target weed and crop plant sizes

The rotary tine weeder has the most aggressive weeding action of the three contiguous weeders and so can control the largest range of weed sizes, potentially up to six true leaves. As with the other weeders, variables such as soil tilth, crop type, size and tolerance to weeding and weed species, etc., will effect the weed sizes that can be controlled. Even though larger weeds can be controlled, as described in section 2.4, weeding should always aim to target cotyledon stage weeds. Controlling weeds at bigger growth stages should only be a last resort.

Crop plants, particularly broadleafs (dicots), are often considered to be quite, to highly, susceptible to rotary tine weeders between shoot emergence from the seed and two to three true leaves, due to their more aggressive action. However, there is no known research that measures crop population reductions and yield impact from rotary tine weeders around crop emergence. Farmers use of rotary tine weeders shows that if they are used slowly, particularly very slowly (less than 2 kph / 1.5 mph), then the shoots of even newly emerged crop plant have the opportunity to bend between the tines. Yet again, doing your own trials is essential (section 2.10).

Once crop plants are larger and more strongly rooted, they are much less likely to be directly uprooted (i.e., pulled out) by rotary tine weeding. The key issue is considered to be foliage damage at moderate and especially higher speeds due to the small spacing between the tines on the wheels and that the wheels are rotating, such that the spokes are likely to catch and rip leaves. This could include uprooting plants by pulling on the foliage. However, if the weeder is used very slowly, e.g., less than 4 kph / 2.5 mph down to 1 kph / ½ mph, the crop foliage, even leafy crops such as beets, have time to pass between the tines with very little damage. At faster speeds even cereals will loose a lot of leaf. See URSUS C 330 & chwastownik obrotowy w uprawie buraka cukrowego - czerwiec 2021 www.youtube.com/watch?v=a0WMKeq3wRY and Einböck Aerostar-Rotation in Uien_2017 www.youtube.com/watch?v=_pu1zUQi-Ek for examples of slow speed operation and Rotative weeder - EINBÖCK AEROSTAR-ROTATION https://youtu.be/nBWlE5n0Q-Q?t=166 for the effects on cereal foliage at higher speeds.

4.5. How it works (mode of action) and how to use one

While superficially similar to a rotary hoe, with both consisting of a number of spoked wheels the mode of action is completely different, being essentially the same as the spring tine weeder (Figure 8). The heart of the rotary tine weeder are the spoked wheels. These are around 50 cm / 25" in diameter consisting of a central hub from which straight, round, stiff, steel tines around 7 mm / ¼" diameter are fixed (Figure 22). The wheels' offset to the direction of travel means that they are forced to turn at a slower speed than tractor forward speed so the tines rake through the soil surface (Figure 22). This results in the tines moving diagonally to the crop row, in approximately the same direction as the wheel's axis of rotation.

The wheels are spaced about 15 cm / 6" apart so there is overlap between adjacent wheels (typically the end of the spokes overlap to the center of the adjacent wheel), consequently the whole field surface is weeded. The best way to fully appreciate the mode of action is to watch it on the videos listed above.

As the wheels rotate the ends of the tines are pushed into the soil nearly vertically (Figure 22, bottom left photo and Figure 24). As the tines are around 7 mm / ¼" in diameter and with downpressure of up to 25 kg per wheel, it means the tines can push into pretty hard soils (see URSUS C 330 & chwastownik obrotowy w uprawie buraka cukrowego - czerwiec 2021 www.youtube.com/watch?v=a0WMKeq3wRY cited above). This is why the rotary tine weeder has much greater penetration and ability to work harder soils that the spring tine weeder where tines

tend to ‘skate’ on hard soils unless the tine is angled aggressively forward and very significant downpressure is applied, which may harm crop plants.

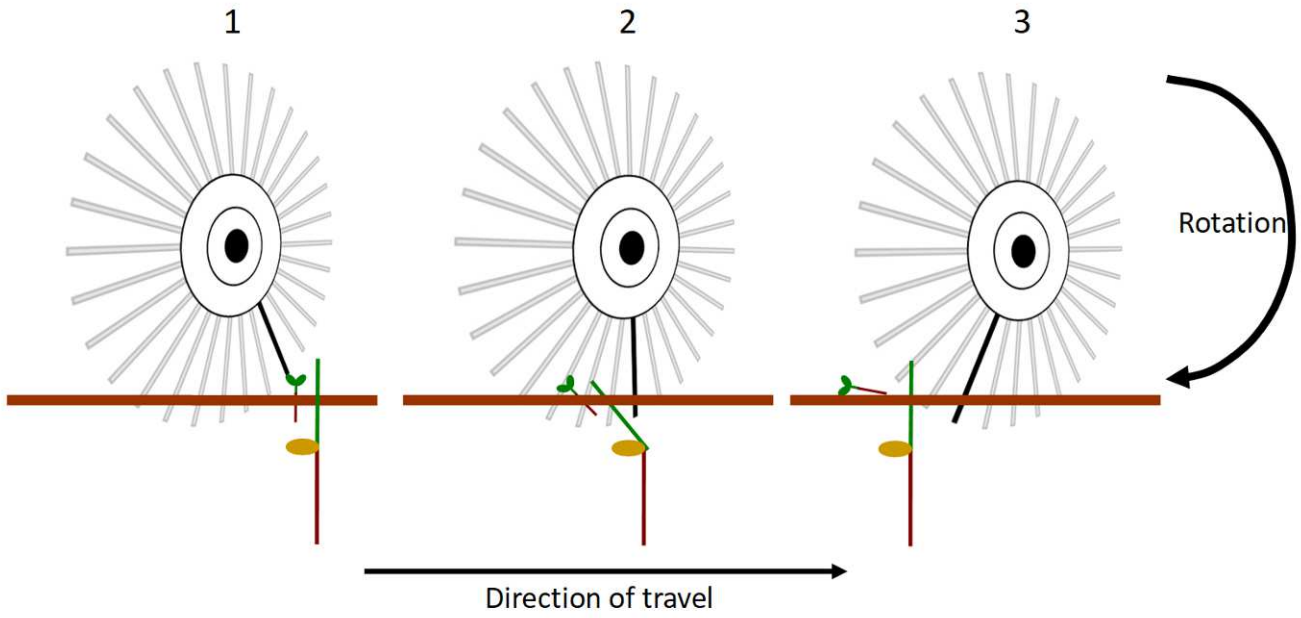


Figure 24. Rotary tine weeder mode of action. The spoked wheels are angled at around 30° to the direction of travel such that they rotate more slowly than forward speed. Consequently the spokes rake through the soil surface as they turn while at the same time being pulled through the soil (No. 1). Tine depth must be shallower than crop seeding depth (No. 1). The rotating tines initially tend to push the crop foliage sideways and downwards as they descend towards the soil surface, while starting to comb out the weeds and rake up residue (No. 2). Then as the tines lift up and away from the soil surface they tend to lift the crops’ foliage back up again, ripping it off at higher speeds, while also finishing combing weeds out of the soil (No. 3).

Fundamentally the rotary and spring tine weeders have the same mode of action with the ends of the tines raking horizontally through the soil surface (Figure 24). The difference is the spring tine weeder the tines are moving directly forward and are independent of each other so can more easily skip over hard soil, crop plants and other obstacles. For the rotary tine weeder the tines are moving diagonally and as the tines are joined together at the hub so there is limited ability for individual tines to skip over obstacles. Only the whole wheel can pivot upwards over larger obstacles, individual tines will thus push through obstructions.

In addition the purely forward motion of the spring tine weeder, and its part reliance on soil throw, means it is more likely to flatten crop foliage and cover it with soil. The turning action of the rotary tine weeder means that crop foliage is initially pushed downwards and then lifted upwards as the wheels pass, such there is a mix of impacts (Figure 24). This is in direction contrast with the rotary hoe where the spoons have no horizontal movement, rather the movement is entirely vertical (Figure 31). Research is required to confirm how the spring and rotary tine weeders differ in their impact on crop foliage, the amount of crop soil cover (CSC, section 2.9.1) they create, and exactly how applicable spring tine weeder CSC research is to rotary tine weeders with their differing effects on crop foliage.

Intuitively it feels that with the rotating-raking action of the tines that the distance between tines passes down the row would be very small, even overlapping. However, this is not the case as https://youtu.be/a0WMKeq3wRY?t=156 shows there is a couple of centimetres / inch gap down the crop row between each tine pass. This is pretty similar to the gap between adjacent spring tine weeder tines. Interestingly the intrarow rotary tine weeder in the left photo in Figure 23 that uses hay-bob tines has two rows of tines offset to each other, such that it halves the gap between each tine pass.

4.5.1. Forward speed

As described above, as tractor forward speed increases the rotational speed of the weeding wheels also increases, with the potential to cause significant crop damage / leaf removal. At slow speeds the crop foliage has time to fold and bend through the narrow gaps between tines with minimum damage. As speed increases the tines start ripping leaves off, particularly as the tines lift upwards from the soil. This contrasts with the spring tine weeder where the gaps between adjacent tines, both front to back and side to side are tens of centimetres / tens of inches, so there is a lot more space for crop plants to bend around individual tines.

At slow speeds the raking action of the wheels mainly stirs the soil as the tines pass through with limited soil throw minimising CSC. As speed increases the tines start throwing more soil around so CSC will increase, particularly for smaller crop plants. The soil and residue throw is mostly sideways due to the rotation of the wheels, with the potential for lines of soil and especially residue to be created which may end up on crop rows harming small plants. Faster speeds therefore has the potential to significantly increase crop harm including yield, both due to foliage damage and increasing CSC. The strong message with rotary tine weeders is: start slow, even very slow, and gradually increase speed until crop foliage damage starts to occur and/or excess CSC, and then back off a bit.

The rotary tine weeder is considered less dependent on speed to kill weeds than the spring tine weeder, with the latter relying more on thrown soil (Figure 13). This is because the weeding wheels are ground driven, thus, they rake through the same area of the soil surface mostly independent of speed. The ability to kill weeds at slow speeds also contrasts with the rotary hoe where faster speeds only slightly increases crop damage but faster speed increases soil throw which increases weed kill considerably.

There is however, no known research on the effect of rotary tine weeder forward speed on weeding efficacy and crop harm including yield (indeed there are only a handful of rotary tine weeder research publications in total). The effects are thus likely be crop species specific, e.g., cereals vs broadleaf crops such as rape. So, once again, undertaking your own trials (section 2.7) will be important to understand the effects.

Slow speeds, especially below 4 kph / 2.5 mph are clearly going to considerably reduce work rates. Where higher work rates are required a spring tine weeder is likely the better option, particularly in larger crop plants to minimise damage to foliage. Better still, move to an incontiguous row-hoe (section 6).

4.5.2. Downpressure

Increasing downpressure is important for improving weed control but it has much less impact on the crop. First, A greater working depth will increase the amount of the weeds' underground parts, particularly the seed and root system, directly impacted by the tines, thus increasing weed kill. Increasing depth also increases the amount of soil disturbance which also increases weed kill, especially small weeds. Second, the working depth should always be above the crop's seeding depth and thus the crop's root system, so the extra weeding depth should not affect the crop's seed or roots. In addition higher downpressure has next to no impact on how the crop's foliage flows through the weeding wheel's tines, that is almost entirely determined the rotational speed of the wheels. Hence why increasing downpressure increases weeding efficacy but has minimal impact on crop foliage, in contrast with the spring tine weeder.

For most designs downpressure is typically controlled by a spring system pushing, pulling or both on the swing arms onto which the wheels are mounted. Some manufactures also have hydraulic systems to control downpressure. This allows for on-the-move downpressure adjustment, which the same as

for spring tine weeders, can be valuable to adapt to varying field conditions such as weed pressure, crop size and soil hardness.

Where manufactures have specified downpressures they range from a few hundred grams / 8 oz i.e., floating, up to 25 kg / 55 lb. The latter is a very large amount of downpressure considering the ends of the tines are being pushed into the soil, hence why rotary tine weeds can penetrate harder soils.

Working in conjunction with the spring tension is the toolbar height because as the weeder is lowered closer to the ground it will increase spring pressure which will in turn increase downpressure and vice versa. Particularly on weeders without hydraulic spring tension adjustment, raising and lowering the weeder on the three point linkage will allow on-the-move downpressure adjustment. However, there are limits to how much the downpressure can be changed by altering toolbar height as there is a limit to how far the swing arms can move. If the three point linkage height is too close to either end of the swing arms' range of movement, then that will limit the ability of the swing arms to compensate for ground undulations and lift over obstacles in the field, like rocks. Obviously the three point linkage cannot be used for downpressure adjustment on the move where the weeder has depth wheels.

4.5.3. Wheel angle

On most rotary tine weeders the angle of the wheels can be changed which will change weeding intensity. Obviously if the wheels are in line with travel there will be no weeding effect as they would simply roll with the direction of travel at the forward speed of the tractor. If the wheels were at 90° to travel direction, they would scrub / not turn at all. Therefore the closer to travel direction the less intensive the weeding action and the closer to 90° the more aggressive the weeding effect. That includes the path adjacent tines make through the soil being closer together. One trade-off is that as the wheels are turned closer to travel direction the overlap between wheels will decrease to the point there is no overlap. However, there is no known independent assessment of changing wheel angles so undertaking your own trials (section 2.7), including on field areas without crop, will once again be essential.

4.5.4. Speed, downpressure and wheel angle interactions

Forward speed, downpressure and wheel angle all interact, however, the level of interaction is not deemed as significant as spring tine weeders.

Out of the three adjustments forward speed is considered to be the key factor for crop damage, as faster speeds are more likely to rip crop foliage, while at slow speeds even leafy crops can be weeded. In these situations increasing downpressure and angling the wheels more across the direction of travel while going slowly will maintain, even increase weeding efficacy while minimising crop damage.

Speed is considered to be a lesser (but not unimportant) factor in weeding efficacy, as the tines rake through a similar volume of the soil surface as they rotate because they are ground driven, so apart from increased soil throw the weeding action is similar within reason for increasing speed.

In short, increasing downpressure will increase weeding efficacy while increasing speed will cause greater crop foliage damage.

4.6. Incontiguous weeding

On designs where swing arms / wheels can have their downpressure individually adjusted and/or be fully lifted clear of the soil, a rotary tine weeder could be used as an incontiguous weeder similar to a spring tine weeder (section 3.16). However, as each wheel has a typical working width / spacing of 15 cm / 6" and the wheel centers may not align perfectly with a crop row, such that two adjacent wheels may need to be lifted for each crop row. This means potentially a significant proportion of the total field surface could receive reduced weeding intensity or no weeding at all resulting in less

effective weed control. This compares with a spring tine weeder where the lateral gap between adjacent tines is just a couple of centimetres / inch allowing a tightly controlled intrarow area. For these reasons using a rotary tine weeder as an incontiguous weeder is generally not considered a viable option and no there are no known examples of rotary tine weeders being used incontiguously.

4.7. Ridge weeding

Likewise, there are no known examples of rotary tine weeders being used on ridge crops, e.g., potatoes. Due to how the weeder works it is considered unsuitable for weeding ridges and best used on flat(ish) ground.

4.8. Side thrust, weeding gap and extra weeding wheels

As the wheels are angled they generate side thrust so Newton's third law (for every action, there is an equal and opposite reaction) applies. Most rotary tine weeders therefore have equal numbers of wheels on the left and right side of the weeder angled in opposite directions so overall side thrust cancels out. This means that there will be an unweeded strip down the center of the machine where the two sets of opposing wheels have to be kept separate or they will hit each other. The typical solution for this is to have one or more extra set of wheels, set further back or in front of the main sets of wheels to weed this strip (Figure 25). For small, e.g., less than 2 m / 2 yard wide weeders, side thrust can be counteracted by depth wheels or the three point linkage.



Figure 25. Extra set of weeding wheels to weed the gap between the two main sets of left and right facing wheels. Set in front (left) photo credit www.feelcrop.com, and behind (right) photo credit www.einboeck.at.

4.9. Working conditions

4.9.1. Soil

Rotary tine weeders can weed a wider range of soil moistures than spring tine weeders and rotary hoes. As long as the soil is dry enough that it can be at least stirred around by the tines, it will be able to cause damage to the weeds. Clearly as soils approach a plastic state then a rotary tine weeder will make a mess, the same for all contiguous weeders, as the tines will just cut through the soil rather than mixing it.

Due to the tines being forced end on into the soil, rotary tine weeders can work in much more compacted soils, including thick caps / crusts than spring tine weeders. Consequently, having a fine surface tilth is therefore less critical than for a spring tine weeder. But if the soil breaks up into larger clods these may damage crop plants and allow weeds to survive on the moisture inside the clod. So while a fine tilth is not essential, rough tilths will reduce weeding efficacy.

4.9.2. Weather

Rotary tine weeders face similar weather limitations to spring tine weeders but they may be able to still effectively work in wetter conditions due to the more intensive weeding action.

4.9.3. Residues

Rotary tine weeders can work in higher residue levels than a spring tine weeder but not as much residue as rotary hoes, especially high residue versions. As the wheels turn they will rake residue across their width. But because the tines the exit the soil as the wheels turn the residue is 'dumped' off the wheel, similar to a hay rake (hay rakes have been used for weeding!). Unlike a hay rake the wheels are arranged such that residue, and other material like stones, are not passed from one wheel to the next but pass between them. Where residue in impaled on the tines it can build up and become a problem. Some weeder designs have scraper systems to clear residues off the tines, as well as stones and clods that get stuck between the tines (Figure 22, top right photo). This contrasts with the spring tine weeder where the tines are in continual contact with the soil (until lifted at the end of the field), so any residue on spring tine weeders cumulatively collects on the tines.

Residue will however be raked into lines, one line of residue for each wheel, not a single line of residue for the whole machine. Where there is a lot of residue there is the potential for the lines to end up on crop rows burying and harming, even killing, small crop plants. Higher speeds result in the residue being thrown from the weeding wheels and spread more evenly reducing this risk.

4.9.4. Stones and clods

The issues that applies to residues also applies to stones and soil clods. The rotary tine weeder will generally continue to achieve good enough weeding in stonier and more cloddy fields than a spring tine weeder as the wheels sweep stones and clods in front of them and individual tines cannot skip over smaller obstacles, they have to push through them. As noted above in residue, stones and clods can get stuck between the tines on the wheels, which could be an issue and some weeders have cleaning systems to remove these.

Where fields are very stony, and for larger individual stones, the weeding wheels will be pushed up out of the ground and roll over them. Clearly when the wheels are pushed out of the soil they can't kill weeds, so there is a limit to the amount of stones before weeding becomes ineffective.

Generally rotary tine weeders will not be damaged by stones as they will roll over them, similar to how spring tine weeder tines will lift up over stones.

4.10. Crop plant clearance

Rotary tine weeders have the lowest crop plant clearance of the three contiguous weeders. The crop has to fit under the hub of the weeding wheels and between the spokes. The length of the tines sticking out from the central hub is about 30 cm / 12" which is the key measurement that limits crop height. Crops need to be able to fit / bend under this height to pass under and through the spokes on the wheels. For broadleaf crops that fill out sideways like beans such as soya, maximum height may only be 20 cm / 8". For taller flexible crops such as maize / corn and cereals such as wheat, 30 cm / 12" high crop plants may be able to be weeded, if at much slower speeds. However, as discussed in section 2.15 research indicates that using tine weeders at later crop growth stages can reduce yield. Further as discussed in section 4.5 faster speeds increasingly shred crop foliage. Both these put additional limits on the height of crops that can be practically and economically weeded. Therefore, a more practical and safe maximum crop height is closer to 10 cm / 4" than the above heights. As discussed in sections 2.2 and 6 it is far better to change to an incontiguous row-hoe at larger crop sizes than persist in using contiguous weeders.

4.11. Perennial herbaceous crop spring cleanup

One niche for the rotary tine weeder is a spring 'cleanup' of perennial herbaceous crops that go dormant over winter i.e., that loose their foliage. The key requirement is that the overwintering buds from which the plant regrows its foliage are not too close to the surface, i.e., they are below the working depth of the rotary tine weeder, so this excludes crops such as mint with surface rhizomes / stolons. Due to its ability to penetrate harder soils which are common after winter, weed aggressively, and disturb the whole soil surface, the rotary tine weeder could clean up over wintered weeds in these crops. Any taller vegetation will need to be grazed or mown down to a low height, and it may well take several passes on the most aggressive settings to achieve sufficient weed kill, but the potential is there.

5. Rotary hoe

5.1. Key points

- The rotary hoe (RH) consists of a series of spoked wheels with the ends of the spokes angled downwards and flattened into a spoon shape. The wheels run parallel to the direction of travel. The wheels are mounted on swing arms attached to a main toolbar.
- The RH was first patented in the USA in 1893 with a long evolution into the modern design which appeared around the 1970s. Over thirty manufactures produce RHs indicating their widespread uptake by farmers and their value as mechanical weeders.
- However, the RH is only really effective against emerging and newly emerged (cotyledon stage) weeds. It can, within limits, be used in crops both immediately before and after emergence, when tine weeders are more likely to cause crop damage. It therefore has a niche from drilling to when crops have their first true leaves.
- The RHs mode of action is completely different to the tine weeders being almost entirely vertical lifting with no, or very limited, horizontal movement through the soil. This is coupled with the substantial soil rain produced that lands on small weeds killing many. This is how it can be used around crop emergence with limited damage and why it only kills the smallest weeds.
- Another key ability of the RH is the ability to break up soil caps / crusts with many farmers rating this to be as important as weeding. It can also therefore penetrate hard soils, though unless these break up into a reasonable tilth, the ability to kill weeds will be more limited.
- Of the three weeders the RH is most dependent on warmer dryer weather to be effective.
- The RH is famous for its ability to work in substantial residue, with there being specific high residue designs.
- Stones however are the enemy of RH due to causing damage and increased wear of the critical spoon tips. While small amounts of gravel wont impact performance larger sizes and greater volumes of stones will hamper weeding efficacy.
- While a RH can work in crops up to around 20 cm / 8" tall, as a RH's niche is around crop emergence and they are only effective against small weeds, in most situations they are not used in larger crops.
- RH are being used for incontiguous weeding (off a very small base) including ridge weeding, but they are not suited for such use unless specifically designed.
- A handful of manufactures have reversed the wheel direction. It is not clear why they have done this, all analysis indicates that it will (significantly) reduce weeding and crust / cap breaking efficacy. There is however no independent testing of normal and reverse wheels.

5.2. Rotary hoe design

The rotary hoe consists of two banks of spoked wheels, with the spokes extending out of the rim, the ends of which are angled downwards by around 30° and flattened into a spoon shape (Figures 26 & 30), hence the alternative name 'spoon weeder' used in countries where rotary hoe means a rotovator / rotary tiller / rotary cultivator (Coleman *et al.*, 2020).

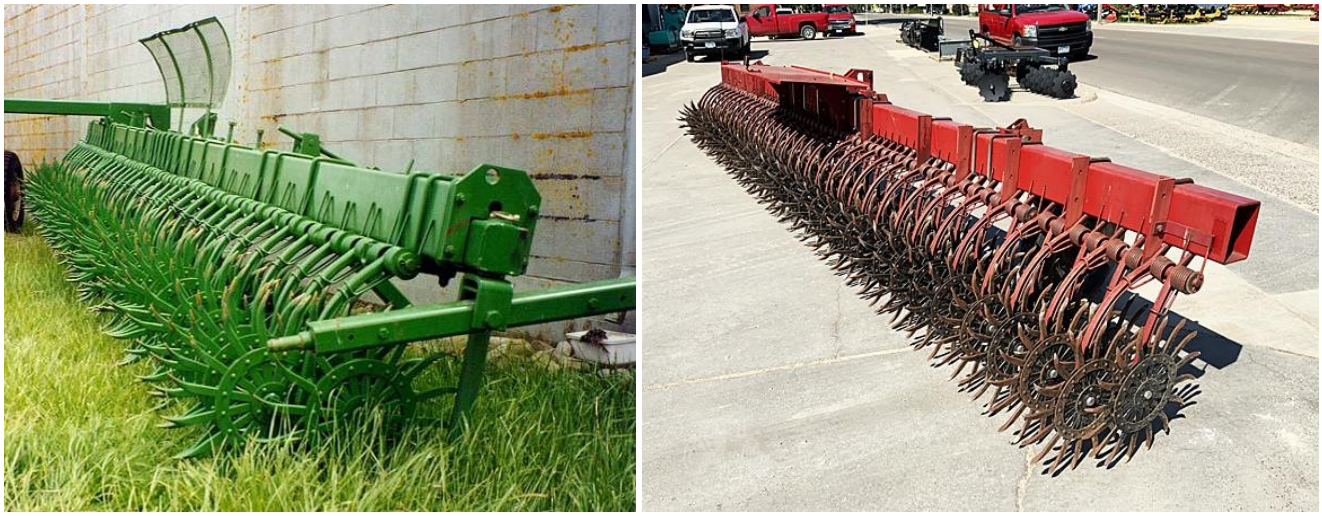


Figure 26. Rotary hoes. John Deere (left), Case IH (right) photo credit www.tractorhouse.com.

5.3. History and origins

The origins of the rotary hoe date to the 1890s when William L. Nieman and William Hieronymus were granted US Patent No. 510,812 for a 'Cultivator' which in the 1890s meant a weeding machine (Figure 27).

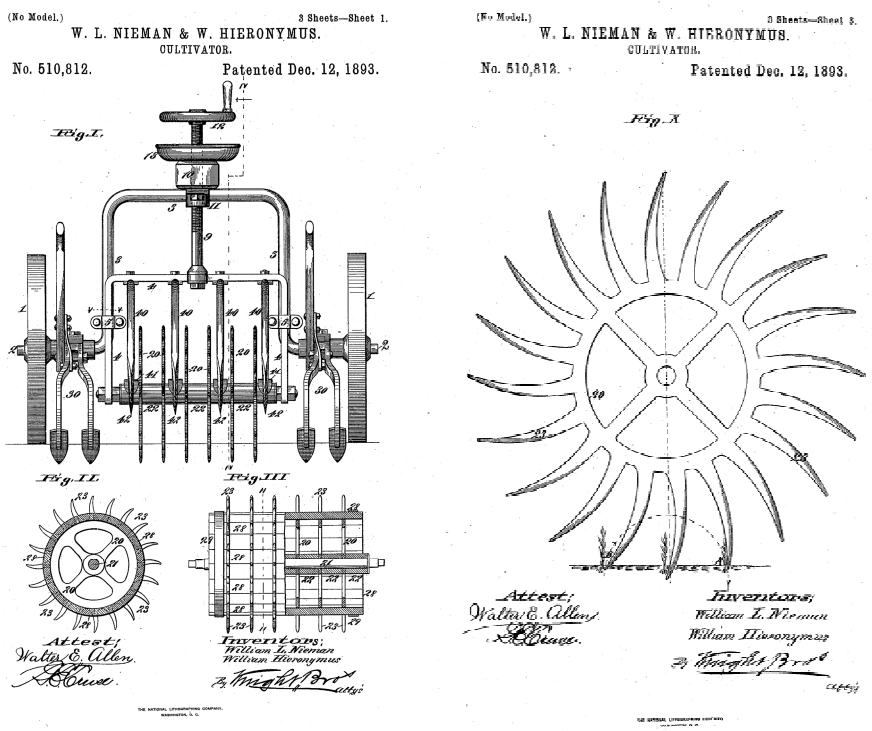


Figure 27. US Patent No. 510,812 (1893) inventors William L. Nieman and William Hieronymus, for a 'cultivator' i.e., rotary hoe. Image credit www.rotary-hoe.com/wp-content/uploads/US-Patent-510812-für-die-erste-Rotary-Hoe-Version-vom-Dezember-1893.pdf, www.rotary-hoe.com/geschichte/.

(Gray, 1929) cited in (Peters *et al.*, 1959) states that rotary hoes date to 1839 based on patents, however as 1839 is likely a typo of 1893, the date on the Nieman and Hieronymus patent, this is likely to be an error. Shawl (1928) also states that Nieman invented the rotary hoe in 1890 saying "It was designed to break up the soil crust, stir the soil close to the young plants, allow air and light to warm the soil and destroy the young weeds just starting to take root." (Shawl, 1928).

According to Nieman and Hieronymus' patent, the purpose of the rotary hoe was:

> "...loosening up of the earth in and about the plant, and the plant will not be uprooted, while at the same time very small weeds, which have surface roots only, will be destroyed." (www.rotary-hoe.com/wp-content/uploads/US-Patent-510812-für-die-erste-Rotary-Hoe-Version-vom-Dezember-1893.pdf)

There is debate if rotary hoes were initially developed for breaking up soil crusts / caps or weeding, but the patent shows that weeding was the main purpose, with breaking up the soil a secondary consideration. However, breaking soil crusts was, and still is, an important use of rotary hoes.

Rotary hoes are generally considered to have been in common use since the early 1900s e.g., (Shawl, 1928; Peters *et al.*, 1959) (Figure 28).

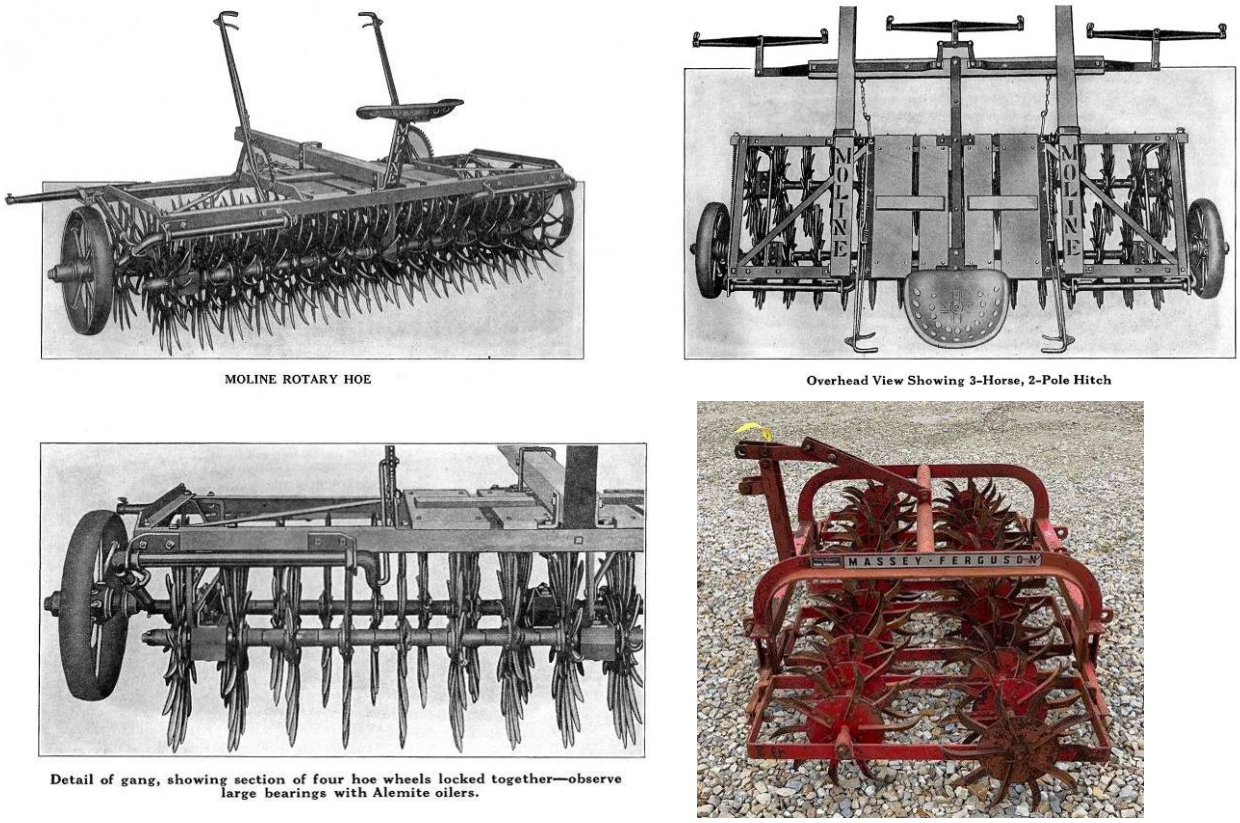


Figure 28. Early 1900s horse drawn rotary hoes. Moline rotary hoe from 'Moline Flying Dutchman Farm Implements. General Catalogue No. 60. Moline Implement Company, Moline Illinois.' (top row, and bottom left) image credit www.smallfarmersjournal.com/rotary-hoes-vs-cultimulchers, Massey Ferguson USA early tractor mounted rotary hoe (bottom right) photo credit www.schneiderauctioneers.com.

Since the early 1900s there have been many patents issued for rotary hoes resulting in the early designs in Figure 28 evolving into the standard design shown in Figure 26.

Until the 2010 rotary hoe production and use was almost entirely limited to N. America with John Deere, Case IH and Yetter dominating along with a few other manufacturers (Bowman, 1997). Prior to the start of the herbicide era in the 1950s most arable / row crop farms in N. America were using rotary hoes (Practical Farmers of Iowa - Rotary Hoes - Organic Weed Control www.youtube.com/watch?v=E5YIWo-LBXk).

Since the start of the 2010s, with the rapid expansion of mechanical weeding in Europe, plus the entry of mainstream agricultural machinery companies into the weeding machinery sector, an increasing number of European manufactures, currently numbering over 30 are producing rotary hoes, some with novel features (Figure 29). This rapid increase in the number of companies

producing rotary hoes shows that farmers are purchasing and using them, so it is taken as a strong indication that they are proving effective on-farm.



Figure 29. KUHN Starliner using a traditional design (left) photo credit www.profi.de, Einböck ROTARYSTAR with novel section based, hydraulic, parallelogram depth / downpressure control system (right) photo credit www.einboeck.at.

5.4. Target weed and crop plant sizes

The total amount of the soil surface, and thus weeds directly impacted by the spoons (i.e., dug up and thrown in the air) is only around 50%, the rest of the weeds are killed by the rain of soil. Consequently rotary hoes are typically only effective on the smallest weeds, immediately prior to emergence and at cotyledon stage. At this point their root systems are poorly developed and not well anchored, their small foliage is more easily buried and/or their hypocotyl is broken. It is widely viewed by both farmers and through research that once weeds have true leaves the effectiveness of rotary hoes for weed management rapidly diminishes.

In addition rotary hoes are generally more effective against small seeded weeds, e.g., less than 3 mm / 1⁄32" as these can only emerge from the top 3 cm / 1" or so of the soil. They are less effective against larger seeded weeds and crop volunteers that are emerging from deeper in the soil profile (Gunsolus, 1990).

In comparison with tine weeders, rotary hoes generally have a small direct negative impact on crop plants, as long as they are seeded deeper than the weeding depth of the hoe. There is no known research on this high level of selectivity (section 2.9) and why it differs from the tine weeders. However, it is proposed that it is the vertical weeding action of rotary hoes (see section 5.5 below) vs. the horizontal weeding action of tine weeders, that is responsible for this difference.

This limitation of only being effective against small weeds but limited crop damage means that rotary hoe use is mainly restricted to pre-crop emergence (pre-em weeding, section 2.19) and immediately post-crop emergence i.e., around crop emergence. This is the same period when the tine weeders are considered to be at the highest risk of damaging the crop.

As the rotary hoe to a large part relies on deeper seeding depth of the crop (section 2.11) than the shallow emerging weeds it can only be used in larger seeded arable / row crops. It is not suitable for small direct seeded vegetable crops, or vegetables in general, due to the amount of soil thrown onto the crop (section 2.24).

While the rotary hoe usually causes little crop damage, where multiple passes are made research (both pre-em and post-em) reasonably strongly indicate that crop populations are reduced (Peters *et al.*, 1959; Leblanc & Cloutier, 2001a, 2001b; Leblanc *et al.*, 2006). Where populations were reduced, some trials found yield was unaffected, potentially as the population reductions were sufficiently small that the arable / row crops were able to compensate. However, this does indicate that too many passes of the rotary hoe can reduce crop plant populations with potential negative impacts on

yield. Thus weeding should only be undertaken when there is a need, not just as a precaution, and/or used increased sowing rates (section 2.10) to compensate for crop losses.

As the rotary hoe is principally used pre and post crop emergence the maximum size of crop plants that can be weeded is less important than for the tine weeders. Having said that, where there is a benefit, e.g., crusted / caped soil, the hoe can work in taller crops, particularly cereals, as the wheels push through the crops foliage. Maximum heights for cereals including maize / corn is around 20 cm / 8" and 10 cm / 4" for broadleaf (dicot) crops (Bowman, 1997).

5.5. How it works (mode of action) and how to use one

The fundamental unit of a rotary hoe are the ground driven, spoked wheels. The wheels are either mounted in pairs on a walking axel / beam which is in turn mounted on a sprung swing arm, or singly on an individual sprung swing-arm. The spring arms are in-turn are mounted on the toolbar, which allows downpressure to be regulated to a degree by raising and lowering the toolbar, and also so they follow ground contours (Figure 26). Some European weeders have the ability to manually change individual spring pressure and/or have hydraulic downpressure control. There are typically two 'banks' of wheels so that they can be placed closer together side-by-side without hitting each other, achieving better ground coverage (Figure 26).



Figure 30. Traditional rotary hoe wheel (left) spoon shaped spoke tips (center and right).

The end of the spokes are bent about 30° forwards (on the front side of the wheels) and flattened into a spoon shape (Figure 30). As the wheels rotate, the spoons enter the ground nearly vertically, then as the hoe moves forward turning the wheels, the spoon tip stays stationary in the soil but with the angle of the spoon changing such that the spoons exit the soil close to horizontal, picking up a small cone of soil and throwing it up into the air (Figure 31).

5.5.1. Why the rotary hoe's action is completely different to tine weeders: vertical vs. horizontal weeding action

Key to the rotary hoe's weeding action is that the spoons do not move horizontally through the soil like the tine weeders, they move almost entirely vertically, due to the wheels being ground driven and thus matching the forward speed of the weeder. The action is akin to taking a knife blade, inserting it vertically into the soil about 4 cm / 1½" deep, then levering the flat side of the blade out of the ground to lift up a small cone of soil. This can be a valuable test to see how easy or hard the rotary hoe has to work in given soil conditions. For the tine weeders the nearly vertical tines rake horizontally through the soil surface and the crop's foliage. It is like taking a pencil sized metal rod holding it vertically on top of the soil and then pulling it sideways while pushing downwards into the soil until it is about 2 cm / ¾" deep. This is considered the decisive difference between the rotary hoe and the tine weeders. The later rake their tines horizontally through the soil and crop plants, thus

tending to knock the crop plants over and flatten them (Figure 8). In contrast the rotary hoe is lifting soil upwards from beside the crop plants' stems so keeping the crop upright and unharmed.

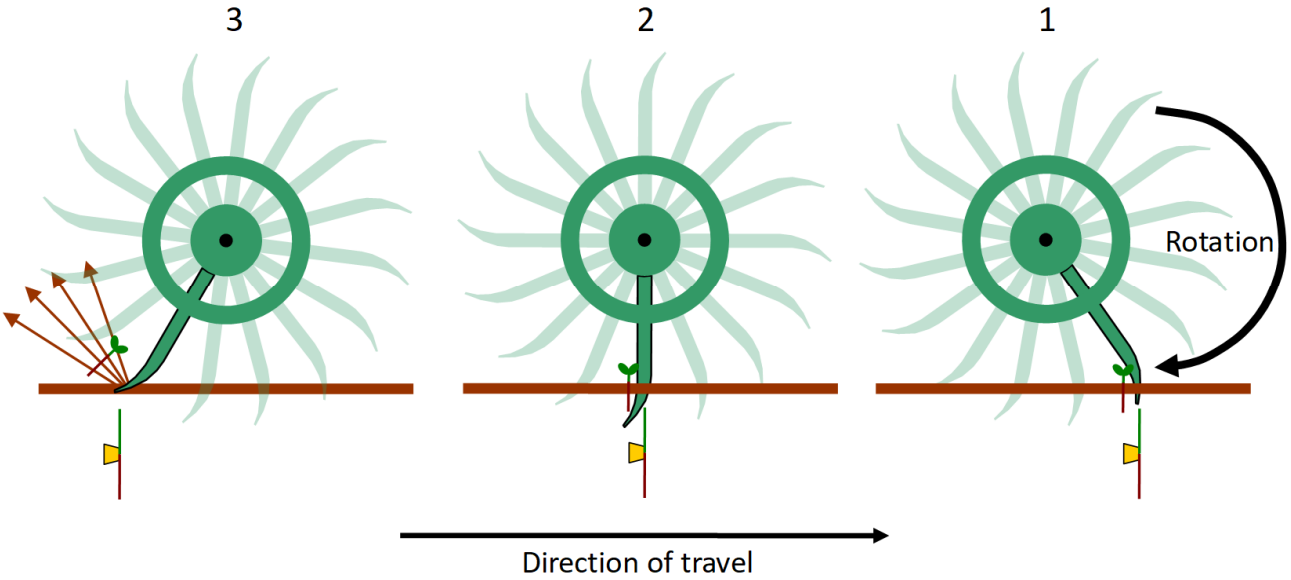


Figure 31. Rotary hoe mode of action. The angled tip / spoon enters the soil vertically (No. 1) then as the weeder moves forward the wheel rotates such that the spoon is stationary in the soil, i.e., it has no horizontal motion through the soil, so is stationary relative to the germinating maize / corn seedling and small weedling. As the wheel rotates to the point that the spoke is vertical, the spoon is now pointing backwards (No. 2) and still positioned above the maize seedling. Then as the wheel continues to rotate the spoon exits the soil nearly horizontally so that it flings the soil and weedling on the spoon into the air while leaving the deeper maize seedling unharmed (No. 3). Note: that the spoon is stationary in relation to the soil and crop is the opposite of spring and rotary tine weeders where the tines are moving relative to the crop (Figure 8).

Generally most crop plants are highly resistant to being pulled vertically, the roots are well anchored and the stem is strong in tension such it resists being pulled apart. This completely different to pushing or pulling a young crop plant horizontally / sideway. They are often (very) easy to knock over, especially cereals like wheat. Thus the vertical action of the rotary hoe works with the vertical strength of crop plants while the tine weeders work against the horizontal weakness of the crop.

Further, with the spoons being pointed there is a low probability of the spoon directly hitting a crop plant and lifting the plant out or breaking the stem. It is much more likely that the crop stem will slide around the spoon as it lifts soil up around the stem. In addition, crop plant leaves generally fold inwards and upwards from their axils. Soil being lifted up from underneath the plant will thus more easily push past the leaves. In contrast, tine weeder tines inevitably directly hit crop stems and leaves bending them over. In addition the spoon working depth must always be shallower than the crop seed so there is no chance of the spoons digging a seed or roots up.

This all combines such that there are only minor sideways forces being applied to crop plants by a rotary hoe, so they stay vertical and are mostly unharmed. They are therefore in the best condition to tolerate (section 2.9) the soil rain falling to the ground with only minimum burial (low crop soil cover (CSC) section 2.9.1). That contrasts with the tine weeders which are applying most of their weeding action as a sideways force on the crop plants bending them, all the way through to flattening them on the ground and then covering them with soil resulting in a much higher CSC. This is why crop plants, particularly pre-emergent and early post emergent, have a high level of resistance (section 2.9) to rotary hoeing while they are much more susceptible to tine weeders.

Accordingly, with it's ability to break soil caps while causing minimum harm to crops due to it's vertical weeding action, but only being effective against cotyledon stage weeds, means that the rotary hoe has a unique position among contiguous weeders of having an operating window of immediately

before and after crop emergence. Thus while it has a narrow window of optimal use, it is the only weeder that can be used in that window with a low risk of crop harm.

5.5.2. Narrowing the wheel gap

Due to the width the wheels, their bearings and the swing-arms, the side-to-side distance between wheels is limited to around 10 cm / 4". This contrasts with the 2 to 4 cm / 1 to 2" horizontal spacing between spring and rotary weeder tines. This larger gap, and due the distance between the spoons around the wheels, means rotary hoes directly impact considerably less of the soil surface that the tine weeders. Thus the spoons on a rotary hoe directly hits the lowest proportion of weeds of the three weeders. Consequently it relies on weeds being both directly dug up by the spoons and then impacted by the large amount of soil thrown up into the air which then lands on the small weeds breaking and/or burying them. This is why worn spoons significantly reduce the efficacy of the rotary hoe and why it is important to replace them when their working width is reduced by more than a quarter.

To address this limitation there are double toolbar rotary hoes, where a second toolbar is positioned behind the wheels of the first toolbar carrying another full set of wheels (or for widely spaced row crops just over the crop row), but offset sideways by half the wheels horizontal spacing so they are weeding the unweeded gap between the first toolbar's wheels (Figure 32, Rotary hoes for grain crop weed management, Rodale Institute https://youtu.be/FHmoISfibZ8?t=2267). However, this makes for a very substantial piece of equipment, with considerable leverage on the three point linkage due to the second toolbar being so far back from the hitch points. Depth / support wheels are likely to be essential!



Figure 32. Double toolbar Yetter rotary hoe. Photo credit www.bidnow.us.

An alternative way to achieve the same result would be to use computer guidance such as RTK GPS autosteer, or better vision based guidence systems (which are more accurate than GPS), to make two passes with a single toolbar rotary hoe, the second pass offset sideways by half the inter-wheel gap. This would most work best by making both passes in the same direction so any unevenness in the gaps between wheels would be automatically compensated for.

5.5.3. Angled rotary hoe wheel designs

One, or very small number of manufactures in N. America, have introduced the ability to slightly change the angle of the wheels to the direction of travel on rotary hoes for intrarow (crop-row) work, akin to a rotary tine weeder (section 4.5). While this may sound like a good idea to increase the weeding action, rather it fundamentally changes the weeding action. Rather than the spoons being stationary relative to the soil and crop and having a vertical soil action, they will start raking

horizontally through the soil, on the diagonal, the same as a rotary tine weeder, while still having the vertical soil action. This could potentially significantly increase crop damage due to the horizontal raking action, especially as it is now the wider spoons raking through the soil not narrow tines. When the angles are very small, e.g., less than 5° the raking effect is likely to be minimal and thus less likely to increase crop damage, but above 5° caveat emptor!

It is recommended that due to the inherent effect of angling rotary hoe wheels to travel direction on their normal mode of action, that theoretical (e.g., computer modelling) and practical research into effects on soil movement, crop harm and weed kill efficacy are required, before angled rotary hoe wheels are used more widely.

5.5.4. Rear spring tines

Some designs have spring tines mounted on the rear of the rotary hoe (Figure 33).





Figure 33. Rear spring tines on a rotary hoe. Left image credit www.rotek-technik.de, right image credit https://ien.kverneland.com.

These are normally promoted on the basis of improving weed control. This is quite likely, as these will further disturb the soil, including breaking up larger pieces that have been dug up by the spoons, which will increase weed kill, although a lot of soil will potentially go over the top of the tines, especially at faster speeds). The tines will also directly hit weeds also killing them, the same as tine weeders. However, the gaps between tines are much larger (and have to be due to space constraints) than on either tine weeder. Thus they cannot fully replicate the effect of either tine weeder, were one to follow the rotary hoe.

In addition rotary hoes have a vertical lifting weeding action while tine weeders have a horizontal raking action (as discussed above). Combining the two 'modes of action' (MoA) highlights why increased weed control is likely, its akin to hitting the same weeds with two different herbicide MoAs. However, a key advantage of the rotary hoe's vertical MoA is that it is far less likely to harm crops than the horizontal MoA of the tine weeders, especially pre-emergence and early crop growth stages. Thus the risk with the rear spring tines with their horizontal MoA is that they could significantly increase crop damage. Thus being able to quickly and easily lift the spring tines off the soil when needed is considered important. Or just not having spring tines on a rotary hoe at all.

5.5.5. Reverse wheel designs

A few European manufacturers have reversed the spoked wheels, so instead of the tip of the spoon entering the soil vertically the back of the spoon enters the soil first nearly horizontally. A very small number of N. America farmers also do this (Rotary hoes for grain crop weed management, Rodale Institute https://youtu.be/FHmoISfibZ8?t=2371).

The effect of reversing the wheels so the back of the spoon hits the soil first, results in it crushing the soil horizontally downwards, rather piercing the soil vertically. And when the spoon exits, as it is now nearly vertical it will throw much less soil into the air. Using the pocket knife analogy used above, it is like placing the knife blade flat on the soil, then levering it downward pivoting around the soil surface

to a depth of around 4 cm / 1½" until it is vertical, and then lifting it out vertically. This action is considered much more likely to trap and crush crop plants under the back of the spoon and bury them in the soil, killing them. Without the soil throw, small weeds that are not directly killed by the spoons are more likely to survive.

The reversed wheel manufactures appear to have a greater focus on soil cap breaking than weeding. One manufacture claims that a much wider area of cracking is achieved for each wheel. However a different manufacturer says that for very hard caped soils the wheels can be reversed, i.e., (re)turned to the normal direction! Reverse wheel manufactures also tout the reduced soil throw as a benefit but when used for weeding the large soil rain is a key part of how weeds are killed (as discussed above). Another manufacturer promotes running the wheels in both directions, standard for crusted soils (i.e., reverse normal direction) and reverse (i.e., normal direction) for stony soils.

However, there is no independent verification of any of the claims reversed wheel rotary hoe manufactures and other proponents make or the weeding efficacy and crop damage from reversing the wheels. It is also unclear why simply reversing the wheel direction would improve weeding efficacy as the normal wheel direction has been in use for over a century and there is sound logic to the design, so it is very unlikely that simply reversing the wheels could improve efficacy, far more likely it will reduce it. Therefore, it is recommended that until there is substantial independent evaluation of reverse wheel designs that caveat emptor applies. You can of course try it yourself!

The rest of this report therefore only covers the standard wheel direction.

5.6. Working conditions

5.6.1. Soil including crusts

Of the three weeders the rotary hoe has the most aggressive soil penetrating action as the spoons are forced vertically into the soil. This means that it can pierce soil crusts / caps and break them up, that would otherwise prevent crop seedlings from emerging. Some consider that the rotary hoe may achieve better weed control in a crust than free flowing soil (Lovely *et al.*, 1958). It can also weed more compacted soil that either tine weeder can, though if soil is very compacted it will be ejecting lumps of soil which have the potential to harm the crop when they land or just punch holes in the soil. A number of research papers testing rotary hoes in conservation tillage found that weed control diminishes considerably compared with fully tilled ground (Hooker *et al.*, 1997, 1998; Bates *et al.*, 2012).

Soils that are approaching their plastic limits, i.e., very wet, are also going to significantly decrease the effectiveness of rotary hoes. However, they can still achieve significant weed control in moist soils. For example, Place & Reberg-Horton (2008) found that weed control increased as soil moved from high, to medium to low soil moisture, but that the differences were only statistically significant between the high and low moisture levels for lower numbers of passes and were not different for the highest number of passes. So, while weed control will nearly always be better in dryer soils, if weeds are at the optimum size for control, i.e., newly emerged / cotyledon stage, but soil conditions are moist, it is better to rotary hoe on time than wait for dryer soils when the weeds have reached true leaf stages.

5.6.2. Weather

Generally the rotary hoe is also the weeder whose effectiveness is most limited by cool and damp weather, but it will still achieve reasonable levels of weed control when conditions are sub-optimal. So as for soil moisture, it is more important to weed at the optimum weed growth stages in inclement weather than wait for better weather and let the weeds get too big because the rotary hoe will not control larger weeds.

5.6.3. Residue

The rotary hoe can cope with the largest amount of residue of all three contiguous weeders, both in terms of thickness and length. Indeed, there are rotary hoes that are specifically designed to cope with high residue levels by having the two banks of wheels spaced further apart to minimise blockages (Figure 34). Residue knifes / cleaner bars can also be fitted to remove residue that is impaled on the spokes (Bowman, 1997).



Figure 34. High residue rotary hoe with much larger spacing between the two banks of wheels to minimise clogging.

'TheFarmersLife - Doing some rotary hoe work with the Deere 4630!' www.youtube.com/shorts/VFvCS1axx3g is an example of the residue level rotary hoes can cope with.

5.6.4. Stones

While rotary hoes can work in soils with some gravel and a few larger stones they are not suited to stony soils. When the pointed tip of the spoon hits a stone it will be blunted and stones will significantly increase spoon wear Figure 35.



Figure 35. Effect of stones on spoon tips.

Worn spoons considerably decrease weeding efficacy as the amount of soil picked up by each spoon decreases with increasing wear, and blunt spoon tips will not be able to penetrate soil as easily reducing working depth.

5.7. Replacing worn spoons

Replacing worn spoons can be a considerable amount of work and /or expense. Where spokes are made of steel (not cast) then the tips can be individually cut off and new tips welded on. For example in N. America there are hardened steel spoons designed to replace worn spoons (Rotary hoes for grain crop weed management, Rodale Institute https://youtu.be/FHmoISfibZ8?t=1871). This has the least consumable cost but a higher labour and time costs. Alternatively all the wheels can be replaced at a higher consumable cost but lower labour cost. For single unit, cast iron wheels, the only practical option is to replace the entire wheel, as welding cast iron is notoriously difficult, especially for a part experiencing the kinds of loads a rotary hoe experiences. Some manufactures have wheel designs where individual spokes are bolted in place (i.e., not permanently fixed), so just the worn or damaged spokes can be replaced, giving a middle ground of medium cost and time to replace them.



Figure 36. Worn (left) and new (right) traditional rotary hoe wheels.

For rotary hoes that get a lot of use / wear the use of tungsten carbide faced spoons is a logical approach, but, there are no known hoes with this option.

5.8. Crop plant clearance

Rotary hoes sit in the middle of crop plant height clearance. The overall theoretical limiting factor is toolbar height as the spring arms and wheels can push between crop plants, thus plants as tall as a meter / yard could in theory be hoed. However, for bushy crops such as beans, the spring arms and wheels will more likely push the crop down, not push through, as they can with maize / corn. However, as the rotary hoe is only effective against the smallest weed sizes, which typically occur when the crop is also small, that it could weed larger crop plants is less relevant that for the tine weeders. Further, as the rotary hoe needs to be used at higher speeds to achieve sufficient levels of weed control, using it at such speeds in crop plants more than 20 cm / 8” high is likely to result in considerable crop damage. One exception to this is where significant soil capping has occurred potentially limiting gas exchange between the soil and atmosphere, in which case a rotary hoe could be used at slower speeds and higher downpressure to break up the soil cap in taller crops.

5.8.1. Incontiguous weeding including ridge weeding

Some manufactures have systems that allow individual wheels or pairs of wheels to be lifted up clear of the ground to allow a rotary hoe to be used as an incontiguous weeder, the same as lifting individual tines or altering their downpressure on a spring tine weeder can turn them into an

incontiguous weeder (section 3.16). A smaller number of manufactures have individual or pairs of wheels independently clamped to the toolbar so semi-permanent crop gaps can be created. This includes gaps big enough for crop ridges, i.e., only the furrow bottoms are being weeded. Likewise some designs allow the downpressure on individual swing arms (thus wheel or pairs of wheels) to be manually adjusted, allowing different downpressures in the interrow and intrarow (crop row). Thus a rotary hoe can be used as an incontiguous weeder with some work. However, all the pros and cons listed for turning a contiguous spring tine weeding into an incontiguous weeder, such as guidence systems, also apply to rotary hoes (section 3.16).

With the ability to adjust the downpressure on individual wheels or wheel pairs it is theoretically possible to adjust downpressure to allow for weeding on ridges, i.e., low pressure on the top of the ridge and high pressure in the furrow. However, due to the level of soil disturbance by rotary hoes, that the soil on ridges is typically pretty soft such that the wheels on the sides of ridges are likely to pull them down, the theory probably does not translate into practice. Only one example of rotary hoes being used contiguously on ridges is known and the ridges were quite flat. It is thus considered unlikely that rotary hoes can be used in a contiguous format on ridges as standard practice. However, there are newer weeder designs using rotary hoe wheels as the weeding tools on the top of ridges using parallelograms and depth wheels (Rotary hoes for grain crop weed management, Rodale Institute www.youtu.be/FHmoISfibZ8?t=1635). So the range of cropping systems where rotary hoes are being used continues to expand.

A logical progression for the current manual individual swing arm downpressure adjustment would the approach taken on a few 2nd generation spring tine weeders where there is remote downpressure adjustment of individual tines. If implemented on a rotary hoe, i.e., the downpressure on each wheel is independently controlled, it would allow for on the fly differential adjustment of downpressure in the interrows and intrarows, allowing for less aggressive weeding in the intrarow and highly aggressive weeding in the interrows. The same for tractor wheelings.

However, the soil rain produced by the rotary hoe falls indiscriminately on both interrow and the crop plants in the intrarow, such there is not the same clear separation between them as there is with an incontiguous spring tine weeder. At the same time due to the vertical weeding action rotary hoes generally cause less crop plant harm. Thus incontiguous weeding with a rotary hoe needs quite a bit of thinking about and experimental testing.

Note: this concept of individual wheel downpressure control is different to the section based hydraulic downpressure parallelogram system of the Einböck rotary hoe shown in the right hand photo in Figure 29.

In addition, where crops are grown on both wide rows / row-crops and narrower standard arable row crop spacings, the ability to quickly change individual swing arm downpressures when moving between different crop ages and layouts could also be valuable.

5.9. Summary of using a rotary hoe

As discussed in section 2.4 the unique action of rotary hoes means it is mainly used immediately pre-crop emergence (pre-em) and immediately post-crop emergence (post-em) when weeds are at the cotyledon stage. Some N. American row crop farmers rate them higher than an interrow-hoe (called a cultivator in N. America) due to being above to operate in that key window (Practical Farmers of Iowa - Rotary Hoes - Organic Weed Control www.youtube.com/watch?v=E5YIWo-LBXk).

For pre-em weeding the aim is to till / cultivate about the top 2-4 cm / ½-1" of the soil, keeping above crop seeding depth, while disturbing as much of the soil as possible. Depending on the duration between sowing and crop emergence more than one pre-em weed could be undertaken. For broadleaf crops, particularly beans, most advice is to avoid weeding once the shoot (plumule) has

emerged until the first true (trifoliate) leaves are out, i.e., avoiding the 'hook stage' as the crop is considered susceptible to the hypocotyl stem breaking which kills the plant. On the other hand, there are a few indications from research and farmers that rotary hoes have been successfully used at the hook stage, but, this should be treated with caution and tested on very small areas of crop before reaching your own conclusions. Cereals may be able to be weeded at all growth stages, but, again, this should be tested on your specific species and cultivars on small areas until you are confident that it is not harmful (see section 2.7).

Once the crop has well developed true leaves then they can be weeded increasingly aggressively, this includes both increasing the working depth by increasing downpressure e.g., up to 5 cm / 2" and speed. However, always work shallower than the seed planting depth and the crops roots. The rotary hoe requires higher forward speeds, e.g., greater than 6 kph / 3 mph up to 30 kph / 20 mph to work effectively as faster forward speeds increases the speed and height that the soil crumbs are thrown and thus increase the damage they do when they hit weeds on the ground.

At the same time faster speeds while increasing the height of soil throw also tends to force the wheels out of the ground, i.e., decrease their operating depth, which will potentially reduce the size the cone of soil picked up by the spoons. Increasing downpressure is thus needed to keep the spoons in the soil as speed increases. However, there is no known research studying these contrary effects so, yet again, more DIY trials are required (section 2.7).

In all cases, checking the effect of the hoe and combination of depth and speed on both crop and weeds is essential. Never just weed and hope for the best. Even once a setting has been established for a given crop / field regularly check that the result is consistent.

Smaller rotary hoes are generally fully three point link mounted so downpressure / aggressiveness can entirely be controlled on the three point linkage. As the spoked wheels are round(!) they are unaffected by toolbar angle (compared with hoe blades that need to be close to vertical) so the weeding action is unaffected by forward and backward tilt of the machine. Accordingly the top link can also be used to control downpressure, by changing the machines tilt. Hydraulic top links are valuable if this approach is taken. Larger, folding machines often have depth wheels, so these control height and therefore downpressure in conjunction with downpressure springs. When front depth wheels only are used, fine adjustments can also be made by changing top link length, thus pivoting the whole weeder on the front depth wheels. Again, making hydraulic top links particularly valuable.

6. Putting it all together

The three contiguous weeders - spring tine weeders, rotary tine weeder, and rotary hoe can be viewed as akin to herbicides with different modes of action (MoA) as proposed in section 2.2. They may be basically doing the same thing — killing weeds across the whole soil surface — but the way they kill weeds and their impacts on the crop and how they cope with different soil and other conditions are sufficiently different that they are both dissimilar and complementary to each other. The same goes for the incontiguous row-hoe (Merfield, 2026a). They should thus be viewed as a mechanical weeding 'package' within an Integrated Weed Management (IWM) system, rather than thinking just one weeder will do the job of all of them. Therefore having all four weeders will give the greatest range of weed killing options and the ability to weed crops at the maximum range of growth stages while causing the minimum harm to the crop, and therefore maximising profitability and long term weed management.

While purchasing four weeders may be financially challenging, especially for smaller farms with limited financial capital, the improved weed control, and particularly decreased weed seed rain, that comes from a superior ability to kill more weeds, across more crops, and crop growth stages, is likely to repay the extra capital expenditure in just a few years. Indeed the return on investment (RoI) could be in the tens of percent, such that borrowing to buy weeders would be profitable.

6.1. Arable / row crops

Focusing in on arable / row crops (rather than vegetables) there is a clear sequence of weeders from pre-planting, through pre-emergence (pre-em) through to post-emergence (post-em).

The two tine weeders are best at implementing false seedbeds (Merfield, 2015), i.e., pre-planting using the most aggressive settings to ensure high levels of weed kill while keeping above the 3 cm / 1" optimum tillage / cultivation depth to minimise bringing up more weed seeds from beneath the emergence zone.

Then for weeding immediately after drilling, as the crop is just putting down roots, the tine weeders will again give better weed control. But once the crop starts to put out a shoot, then the rotary hoe is a safer option as it is less likely to harm crop plants. The same goes for early post-em when the tine weeders are more likely to cause crop harm if used injudiciously.

However, with the typically lower levels of weed control achieved by the rotary hoe, as soon as the crop is sufficiently large and tolerant (from the first true leaves to around three true leaves depending on crop species) then the tine weeders should be the weeder of choice. These should be setup so that soil throw and thus crop soil cover (CSC, section 2.9.1) is minimised when the crop is still small and the most sensitive to weeding. This includes using the spring tine weeder in incontiguous mode (section 3.16). Field conditions, e.g., a fine loose tilth, vs. packed soil and residue will determine if a spring tine weeder or rotary tine weeder are the best option.

Row-hoes can also be used anytime after drilling depending on guidence systems, i.e., computer vision only works once the crop has emerged. Initially intrarow weeding tools should be avoided as they will harm, even kill, the crop. However, the much more aggressive interrow weeding tools will ensure that the interrow is really clean even when intrarow weed control is at its most challenging.

As the crop gets a bit bigger and tougher, then both tine weeders can be used more aggressively though not so aggressively that CSC exceeds 30% and/or crop foliage is overly damaged.

Once the crop is much bigger than 10 cm / 4" swapping over to a row-hoe to finish off the weeding, including using intrarow weeders more aggressively, is the better path forward. There is sufficient evidence that using contiguous weeders as the crop gets bigger may not visually harm the crop but can significantly reduce yield (section 2.15), so row-hoes should be the weeder of choice, from now

on. When the crop gets to around 15 cm / 6” it is essential that all contiguous weeders are replaced with row-hoes.

And finally, depending on the crop and post-harvest objectives the final weeding could also be used to undersow a service crop (Merfield, 2023b).

6.2. Vegetables

For vegetable production, the row-hoe is the dominant mechanical weeding tool, including the use of intrarow weeders such as finger weeders and mini-ridgers. Both tine weeders can then be valuable additions to the row-hoe if and when crop plants are tough enough to withstand the weeding action and provided there is no impact on marketable yield, e.g., through damaged foliage. Tine weeders provide valuable additional weeding tools to take the demand off the row-hoe. As they weed both the interrow and intrarow they can compliment the intrarow weeders on the row-hoe, killing weeds that may have been missed by the row-hoe. They also do not require guidence systems so can be hand-steered if required. But as for arable / row crops, their use is likely best restricted to the first few weeks or month of a crops life as their use as the crop grows may start to negatively impact harvest yield and quality.

7. Conclusions

Contiguous weeders - spring tine weeders, rotary tine weeder and rotary hoe can achieve first-rate levels of weed control when used correctly. When used as part of a wider Integrated Weed Management (IWM) programme, particularly using pre-plant weed control such as false seedbeds (Merfield, 2015) and row-hoes (Merfield, 2026a) excellent weed control can be achieved without any herbicides. When intelligently integrated with herbicides, the strengths of both chemical and mechanical weed management can be leveraged to compliment the weaknesses of both approaches. In combination with smarter herbicide use, mechanical weeding is also a key part of herbicide resistance management.

Thanks to organic farming continuing to use mechanical weeding while mainstream farming switched to herbicides, modern weeding machinery is like an electric car compared with to horse and cart that represents pre-1950’s machinery. It is now possible to buy off the self contiguous weeders up to 30 m / 90’ wide that can be put into immediate use with minimum setup with the ability to weed tens of thousands of hectares / acres. At the same time, the same machinery designs are available for the smallest market gardens, even pedestrian versions are available. Consequently farmers and growers no longer need to fix up old weeders, or modify poor designs. There are now a large range of agricultural machinery manufactures, including some of the worlds largest ag-machinery companies, supplying a range, even a full suite of mechanical weeding equipment. Thus there has never been a better time to get into mechanical weeding, safe in the knowledge that it will be even better tomorrow!

Happy weeding!™

8. Further information

One of the best places to learn more about mechanical weeding (beyond this report!) is YouTube, particularly farmers' channels that are using mechanical weeding at scale, typically but not aways, organic farmers. Plus various more general agricultural channels. They often discuss in detail what works and what does not, with many useful tips on practical use. Some of the key channels I find valuable include (in alphabetical order):

- Crop Fertility Services www.youtube.com/@cropfertilityservices
- Fehrs Farming Organic www.youtube.com/@FehrsFarmingOrganic
- Ferme Wilmots Agriculture Bio www.youtube.com/@fermewilmotsagriculturebio3434
- Hof Vogelsang www.youtube.com/@HofVogelsang with www.youtube.com/watch?v=M8fJev-YUeI giving a very good introduction to setting up a spring tine weeder
- Practical Farmers of Iowa www.youtube.com/@practicalfarmers
- Struve Family Farms Organics www.youtube.com/@struvefamilyfarmsorganics7303

Manufacturers websites also have valuable information, but always with potential bias to their machines and not necessarily with the many thousands of hours of real-world farmers' experience. Einbock deserve special mention as they have some free, comprehensive handbooks www.einboeck.at/en/downloads/?_download_tax=handbooks. There are also a range of research and extension organisations that have useful content. In alphabetical order:

- Century Farm Organics www.youtube.com/@CenturyFarmOrganics
- Einböck www.youtube.com/@einboeck
- FiBL www.youtube.com/@FiBLFilm
- Future Farming www.youtube.com/@FutureFarming1
- GROW IWM www.youtube.com/@GROWIWM
- HAK www.youtube.com/@haknlschoffelmachines6023
- Hatzenbichler www.youtube.com/@TheHatzenbichler
- Landwirt-media www.youtube.com/@landwirtmedia
- Oper8 www.youtube.com/@Oper8/videos
- Organic Agronomy Training Service www.youtube.com/@organicagronomytrainingser8522
- Projekt Mechanische Unkrautbekämpfung www.youtube.com/@projektmechanischeunkrautb7975
- Rodale Institute www.youtube.com/watch?v=FHmoISfibZ8
- SARE www.youtube.com/@SAREOutreach1

The auto-translate caption feature is very valuable for videos in languages you don't understand.

Landwirt-media have also conducted trials on six 2nd generation weeders (in alphabetical order):

- Introduction www.youtube.com/watch?v=uJr2a1gIpXM
- APV Variostriegel VS 1200 M1 www.youtube.com/watch?v=m7y3JOgXuhQ
- DicksonKerner VFS precision harrow www.youtube.com/watch?v=eKVml3wwQEs
- Einböck Aerostar-Fusion www.youtube.com/watch?v=Qiq6l8vjn0M
- Hatzenbichler Air-Flow www.youtube.com/watch?v=5WGtuunA4hU
- Horsch Cura 12 ST www.youtube.com/watch?v=PUd2qGWRRs8
- Treffler TS 1220 M3 www.youtube.com/watch?v=DpV0b4n_MSE&t=1s

And a German agronomist and consultant York-Thorne Bayer has produced a website www.rotary-hoe.com with a considerable amount of information on rotary hoes.

9. References

Bates, R. T., Gallagher, R. S., Curran, W. S. & Harper, J. K. (2012). Integrating mechanical and reduced chemical weed control in conservation tillage corn. *Agronomy Journal, 104*(2), 507-517. doi:10.2134/agronj2011.0140 http://acsess.onlinelibrary.wiley.com/doi/abs/10.2134/agronj2011.0140

Berge, T. W., Urdal, F., Torp, T. & Andreasen, C. (2024). A sensor-based decision model for precision weed harrowing. *Agronomy, 14*(1), 88. doi:10.3390/agronomy14010088 http://www.mdpi.com/2073-4395/14/1/88

Bloomer, D. J. (2023). Alternative weed control methods. Proceedings of the LandWISE 'Normal practice revisited", Havelock North, New Zealand

Bloomer, D. J., Harrington, K. C., Ghanizadeh, H. & James, T. K. (2022). Micro electric shocks control broadleaved and grass weeds. *Agronomy, 12*(9), 2039. doi:10.3390/agronomy12092039 http://www.mdpi.com/2073-4395/12/9/2039

Bloomer, D. J. & Powrie, J. (2013). *Permanent beds for vegetables farmer guidelines*. Havelock North, New Zealand: LandWISE http://www.archive.landwise.org.nz/wp-content/uploads/Permanent-Beds-2013.pdf

Bowman, G. (Ed.). (1997). *Steel in the field: A farmer's guide to weed management tools*. Beltsville, USA: Sustainable agriculture Network http://www.sare.org/resources/steel-in-the-field/

Cloutier, D. C. & Leblanc, M. L. (2011). Mechanical weed control in cereal crops in Eastern Canada. In D. C. Cloutier & M. L. Leblanc (Eds.), *Physical weed control: Progress and challenges* (pp. 35-44). Pinawa, Manitoba, Canada: Canadian Weed Science Society – Société Canadienne de Malherbologie http://www.weedscience.ca/wp-content/uploads/2021/04/Physical-weed-control_-vol-6-cloutier-and-leblanc.pdf

Coleman, G. R. Y., Stead, A., Rigter, M. P., Xu, Z., Johnson, D., Brooker, G. M., Sukkarieh, S. & Walsh, M. J. (2019). Using energy requirements to compare the suitability of alternative methods for broadcast and site-specific weed control. *Weed Technology, 33*(4), 633-650. doi:10.1017/wet.2019.32 http://www.cambridge.org/core/article/using-energy-requirements-to-compare-the-suitability-of-alternative-methods-for-broadcast-and-sitespecific-weed-control/CE8E572179F660512A09F5490094189E

Coleman, G. R. Y., Stead, A., Rigter, M. P., Xu, Z., Johnson, D., Brooker, G. M., Sukkarieh, S. & Walsh, M. J. (2020). Using energy requirements to compare the suitability of alternative methods for broadcast and site-specific weed control – CORRIGENDUM. *Weed Technology, 34*(1), 153-154. doi:10.1017/wet.2019.131 http://www.cambridge.org/core/article/using-energy-requirements-to-compare-the-suitability-of-alternative-methods-for-broadcast-and-sitespecific-weed-control-corrigendum/626A8AD86BD59D8A3FD969D0AED87245

Dastgheib, F., Merfield, C. N. & Chamberlain, T. P. (2010). Post-emergence thermal weeding in onions (*Allium cepa*). *Agronomy New Zealand, 40*, 177-186. http://www.agronomysociety.org.nz/files/2010_16._Post-em_thermal_weeding_onion.pdf

Einböck. (2023). *The organic farming handbook 3rd edition*. Dorf an der Pram, Austria: Einböck http://www.einboeck.at/en/handbooks/

Endres, G., Berglund, D., Dexter, A. & Zollinger, R. (1999). *Mechanical weed control with a harrow or rotary hoe*. Fargo, North Dakota, USA: North Dakota State University http://library.ndsu.edu/server/api/core/bitstreams/140bb150-c0ec-479b-aaa4-7b3543271aff/content

Gerhards, R., Späth, M., Sökefeld, M., Peteinatos, G. G., Nabout, A. & Rueda Ayala, V. (2021). Automatic adjustment of harrowing intensity in cereals using digital image analysis. *Weed Research, 61*(1), 68-77. doi:10.1111/wre.12458 http://onlinelibrary.wiley.com/doi/abs/10.1111/wre.12458

Gray, C. W. (1929). Hoe on wheels. *Breeders Gazette, 94*(38)

Gunsolus, J. L. (1990). Mechanical and cultural weed control in corn and soybeans. *American Journal of Alternative Agriculture, 5*(3), 114-119. doi:10.1017/S0889189300003416 http://www.cambridge.org/core/product/C95762C383194FA75A09DF1CEC1441B1

Hooker, D. C., Vyn, T. J. & Swanton, C. J. (1997). Effectiveness of soil-applied herbicides with mechanical weed control for conservation tillage systems in soybean. *Agronomy Journal, 89*(4), 579-587. doi:10.2134/agronj1997.00021962008900040008x http://acsess.onlinelibrary.wiley.com/doi/abs/10.2134/agronj1997.00021962008900040008x

Hooker, D. C., Vyn, T. J. & Swanton, C. J. (1998). Alternative weed management strategies in conservation tillage systems for white beans (*Phaseolus vulgaris* L.). *Canadian Journal of Plant Science, 78*(2), 363-370. doi:10.4141/p97-055 http://cdnsciencepub.com/doi/abs/10.4141/P97-055

James, T. K. & Merfield, C. N. (2023). Weed and soil management: A balancing act. In M. J. Goss & M. Oliver (Eds.), *Encyclopedia of Soils in the Environment (Second Edition)* (Vol. 3, pp. 439-449). Oxford: Academic Press doi:10.1016/B978-0-12-822974-3.00007-0 http://www.sciencedirect.com/science/article/pii/B9780128229743000070

Jensen, R. K., Rasmussen, J. & Melander, B. (2004). Selectivity of weed harrowing in lupin. *Weed Research, 44*(4), 245-253. doi:10.1111/j.1365-3180.2004.00396.x http://www.blackwell-synergy.com/doi/abs/10.1111/j.1365-3180.2004.00396.x

Kaufman, K. R. & Schaffner, L. W. (1982). Energy and economics of electrical weed control. *Transactions of the ASAE, 25*(2), 297. doi:10.13031/2013.33523 http://elibrary.asabe.org/abstract.asp?aid=33523&t=3

Keller, T., Bickel, S. & Or, D. (2025). The invisible subsoil compaction risk under no-till farming. *Proceedings of the National Academy of Sciences, 122*(46), e2515473122. doi:10.1073/pnas.2515473122 http://www.pnas.org/doi/abs/10.1073/pnas.2515473122

Kurstjens, D. A. G., Perdok, U. D. & Goense, D. (2000). Selective uprooting by weed harrowing on sandy soils. *Weed Research, 40*(5), 431-447. doi:10.1046/j.1365-3180.2000.00205.x http://onlinelibrary.wiley.com/doi/10.1046/j.1365-3180.2000.00205.x

Leblanc, M., Cloutier, D. & Stewart, K. (2006). Rotary hoe cultivation in sweet corn. *HortTechnology, 16*(4), 583-589. doi:10.21273/HORTTECH.16.4.0583 http://journals.ashs.org/view/journals/horttech/16/4/article-p583.xml

Leblanc, M. L. & Cloutier, D. C. (2001a). Susceptibility of dry edible bean (*Phaseolus vulgaris*, cranberry bean) to the rotary hoe. *Weed Technology, 15*(2), 224-228, 225. doi:10.1614/0890-037X(2001)015[0224:SODEBP]2.0.CO;2 http://bioone.org/journals/weed-technology/volume-15/issue-2/0890-037X(2001)015%5b0224%3aSODEBP%5d2.0.CO%3b2/Susceptibility-of-Dry-Edible-Bean-Phaseolus-vulgaris-Cranberry-Bean-to/10.1614/0890-037X(2001)015[0224:SODEBP]2.0.CO;2.short

Leblanc, M. L. & Cloutier, D. C. (2001b). Susceptibility of row-planted soybean (G*lycine max*) to the rotary hoe. *Journal of Sustainable Agriculture, 18*(4), 53-61. doi:10.1300/J064v18n04_07 http://www.tandfonline.com/doi/abs/10.1300/J064v18n04_07



Liebman, M. & Gallandt, E. R. (1997). Many little hammers: ecological management of crop-weed interactions. In L. E. Jackson (Ed.), *Ecology in Agriculture* (pp. 291–343). San Diego, CA: Academic Press doi:10.1016/B978-012378260-1/50010-5 http://www.sciencedirect.com/science/article/pii/B9780123782601500105

Lovely, W. G., Weber, C. R. & Staniforth, D. W. (1958). Effectiveness of the rotary hoe for weed control in soybeans. *Agronomy Journal, 50*(10), 621-625. doi:10.2134/agronj1958.00021962005000100017x http://acsess.onlinelibrary.wiley.com/doi/10.2134/agronj1958.00021962005000100017x

Marshall, E. J. P. (2019). Reflections on 14 years as Editor-in-Chief. *Weed Research, 59*(1), 1-4. doi:10.1111/wre.12350 http://onlinelibrary.wiley.com/doi/abs/10.1111/wre.12350

Merfield, C. N. (2006). *Organic F1 hybrid carrot seed (Daucus carota L.) production: the effect of crop density on seed yield and quality, thermal weeding and fungal pathogen management.* PhD Thesis, Lincoln University http://www.merfield.com/research/2006/phd/index.htm

Merfield, C. N. (2015). False and stale seedbeds: The most effective non-chemical weed management tools for cropping and pasture establishment. *The Future Farming Centre Bulletin, 4*, 1-25. http://merfield.com/research/2015/false-and-stale-seedbeds--the-most-effective-non-chemical-weed-management-tools-for-cropping-and-pasture-establishment-2015-ffc-merfield.pdf

Merfield, C. N. (2018). Mini-ridgers: Lethal burial depth for controlling intrarow weeds. *The Future Farming Centre Bulletin, 2018*(V2) https://www.bhu.org.nz/mini-ridgers-lethal-burial-depths-for-controlling-intrarow-weeds-2018-ffc-merfield/

Merfield, C. N. (2022). Redefining weeds for the post-herbicide era. *Weed Research, 62*(4), 263-267. doi:10.1111/wre.12544 http://onlinelibrary.wiley.com/share/author/2XJPNXNTRBFMQHFVPMPI?target=10.1111/wre.12544

Merfield, C. N. (2023a). Integrated weed management in organic farming. In S. Chandran, M. R. Unni, S. Thomas & D. K. Meena (Eds.), *Organic farming: Global perspectives and methods. 2nd Edition* (pp. 31-110). Cambridge, MA, United States: Elsevier Science http://shop.elsevier.com/books/organic-farming/chandran/978-0-323-99145-2

Merfield, C. N. (2023b). An introduction to the principles of service (cover) crops and intercropping. *The Future Farming Centre Bulletin, 3*, 23. https://www.bhu.org.nz/an-introduction-to-the-principles-of-service-cover-crops-and-intercropping-2023-ffc-merfield/

Merfield, C. N. (2026a). Modern (inter)row-hoes. The Swiss army knife of mechanical weeders. A comprehensive guide. V1.1. *The BHU Future Farming Centre Bulletin, 4*, 84. http://www.bhu.org.nz/future-farming-centre/information/bulletin/the-ffc-bulletin-2026-v4-mechanical-weeding-for-annual-crops-a-comprehensive-guide/

Merfield, C. N. (2026b). *Soil health and its management*. The BHU Future Farming Centre http://www.bhu.org.nz/soil-health-and-its-management-2026-merfield-ffc/

Pardo, G., Cirujeda, A., Aibar, J., Cavero, J. & Zaragoza, C. (2008). Weed harrowing in winter cereal under semi-arid conditions. *Spanish Journal of Agricultural Research, 6*(4), 661-670. doi:10.5424/sjar/2008064-358 http://sjar.revistas.csic.es/index.php/sjar/article/view/358

Parks, J. W. & Gallandt, E. R. (2023). Testing a tine weeder with artificial weeds in the controlled conditions of a soil bin. *Weed Research, 63*(5), 328-337. doi:10.1111/wre.12595 http://onlinelibrary.wiley.com/doi/abs/10.1111/wre.12595



Peteinatos, G., Gierer, F. & Gerhards, R. (2018). Precision harrowing using a bispectral camera and a flexible tine harrow. Proceedings of the Tagungsband 28. Deutsche Arbeitsbesprechung über Fragen der Unkrautbiologie und – bekämpfung : 27. Februar - 1. März 2018, Braunschweig, Germany, 385-389. doi:10.5073/jka.2018.458.057 http://www.openagrar.de/receive/openagrar_mods_00036796

Peters, E. J., Klingman, D. L. & Larson, R. E. (1959). Rotary hoeing in combination with herbicides and other cultivations for weed control in soybeans. *Weeds, 7*(4), 449-458. doi:10.2307/4040466 http://www.cambridge.org/core/product/E7522392B52346FFB98DEC850476EF9F

Place, G. & Reberg-Horton, C. (2008). *Rotary hoe: A blind cultivation tool for in row weed control*. Raleigh, North Carolina, USA: North Carolina State University http://content.ces.ncsu.edu/pdf/rotary-hoe-a-blind-cultivation-t/2014-09-29/rotary-hoe-a-blind-cultivation-tool-for-in-row-weed-control.pdf

Rademacher, B. (1940). The control of weeds in Germany. Proceedings of the Herbage Publication Series Bulletin 27, Aberystwyth, Great Britain, 68-112.

Rasmussen, J. (1990). Selectivity - an important parameter on establishing the optimum harrowing technique for weed control in growing cereals. Proceedings of the 1990 EWRS Symposium, integrated weed management in cereals, Helsinki, 197-204.

Rasmussen, J. (1991). A model for prediction of yield response in weed harrowing. *Weed Research, 31*(6), 401-408. doi:10.1111/j.1365-3180.1991.tb01780.x http://onlinelibrary.wiley.com/doi/10.1111/j.1365-3180.1991.tb01780.x

Rasmussen, J. (1992). Testing harrows for mechanical control of weeds in agricultural crops. *Weed Research, 32*(4), 267-274. doi:10.1111/j.1365-3180.1992.tb01886.x http://onlinelibrary.wiley.com/doi/10.1111/j.1365-3180.1992.tb01886.x

Rasmussen, J. (1993). Yield response models for mechanical weed control by harrowing at early crop growth stages in peas (*Pisum sativum* L.). *Weed Research, 33*(3), 231-240. doi:10.1111/j.1365-3180.1993.tb01937.x http://onlinelibrary.wiley.com/doi/10.1111/j.1365-3180.1993.tb01937.x

Rasmussen, J. (2024). Stop wasting time on mechanical weed control research that lacks a theoretical foundation. *Weed Research, 64*(5), 356-364. doi:10.1111/wre.12655 http://onlinelibrary.wiley.com/doi/abs/10.1111/wre.12655

Rasmussen, J., Kurtzmann, J. I. & Jensen, A. (2004). Tolerance of competitive spring barley cultivars to weed harrowing. *Weed Research, 44*(6), 446-452. doi:10.1111/j.1365-3180.2004.00419.x http://www.blackwell-synergy.com/doi/abs/10.1111/j.1365-3180.2004.00419.x

Rasmussen, J., Nielsen, H. H. & Gundersen, H. (2009). Tolerance and selectivity of cereal species and cultivars to postemergence weed harrowing. *Weed Science, 57*(3), 338-345. doi:10.1614/WS-08-109.1 http://www.cambridge.org/core/journals/weed-science/article/abs/tolerance-and-selectivity-of-cereal-species-and-cultivars-to-postemergence-weed-harrowing/983826945AEE7C278DA8435919A6E48F

Rasmussen, J. & Nørremark, M. (2007). Digital images for assessing soil cover of crop plants. Proceedings of the 7th EWRS Workshop on Physical and Cultural Weed Control, Salem, Germany, 123-129. http://orgprints.org/id/eprint/10758/

Rasmussen, J., Norremark, M. & Bibby, B. M. (2007). Assessment of leaf cover and crop soil cover in weed harrowing research using digital images. *Weed Research, 47*(4), 299-310. doi:10.1111/j.1365-3180.2007.00565.x http://www.blackwell-synergy.com/doi/abs/10.1111/j.1365-3180.2007.00565.x

Rasmussen, J., Schou, B. M. & Bibby, A. P. (2008). Investigating the selectivity of weed harrowing with new methods. *Weed Research, 48*(6), 523-532. doi:10.1111/j.1365-3180.2008.00661.x http://onlinelibrary.wiley.com/doi/abs/10.1111/j.1365-3180.2008.00661.x



Riemens, M., Sønderskov, M., Moonen, A.-C., Storkey, J. & Kudsk, P. (2022). An integrated weed management framework: A pan-European perspective. *European Journal of Agronomy, 133*, 126443. doi:10.1016/j.eja.2021.126443 http://www.sciencedirect.com/science/article/pii/S1161030121002148

Robbins, W. W., Crafts, A. S. & Raynor, R. N. (1942). *Weed control: a textbook and manual. (First Edition, Second Impression)*. New York, USA and London, UK: McGraw-Hill Publishing Company Ltd

Rueda-Ayala, V., Peteinatos, G., Gerhards, R. & Andújar, D. (2015). A non-chemical system for online weed control. *Sensors, 15*(4), 7691-7707. doi:10.3390/s150407691 http://www.mdpi.com/1424-8220/15/4/7691

Rueda-Ayala, V., Weis, M., Keller, M., Andújar, D. & Gerhards, R. (2013). Development and testing of a decision making based method to adjust automatically the harrowing intensity. *Sensors, 13*(5), 6254-6271. http://www.mdpi.com/1424-8220/13/5/6254

Rueda-Ayala, V. P., Rasmussen, J., Gerhards, R. & Fournaise, N. E. (2011). The influence of post-emergence weed harrowing on selectivity, crop recovery and crop yield in different growth stages of winter wheat. *Weed Research, 51*(5), 478-488. doi:10.1111/j.1365-3180.2011.00873.x http://onlinelibrary.wiley.com/doi/10.1111/j.1365-3180.2011.00873.x

Rydberg, T. (1994). Weed harrowing—the influence of driving speed and driving direction on degree of soil covering and the growth of weed and crop plants. *Biological Agriculture & Horticulture, 10*(3), 197-205. doi:10.1080/01448765.1994.9754668 http://www.tandfonline.com/doi/abs/10.1080/01448765.1994.9754668

Shawl, R. I. (1928). The rotary hoe. *Agricultural Engineering, 9*(2), 60. http://archive.org/details/sim_agricultural-engineering_1928-02_9_2

Spaeth, M., Machleb, J., Peteinatos, G. G., Saile, M. & Gerhards, R. (2020). Smart harrowing—Adjusting the treatment intensity based on machine vision to achieve a uniform weed control selectivity under heterogeneous field conditions. *Agronomy, 10*(12), 1925. doi:10.3390/agronomy10121925 http://www.mdpi.com/2073-4395/10/12/1925

Spaeth, M., Schumacher, M. & Gerhards, R. (2021). Comparing sensor-based adjustment of weed harrowing intensity with conventional harrowing under heterogeneous field conditions. *Agronomy, 11*(8), 1605. doi:10.3390/agronomy11081605 http://www.mdpi.com/2073-4395/11/8/1605