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Advances in mechanical weed control technologies

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1 Introduction

Mechanical weed control (MWC) for agricultural and horticultural crops encompasses various belowground soil cultivation techniques and aboveground cutting, mowing and weeding tactics. Mowing disrupts aboveground vegetation, immediately eliminates weed competition and hinders the shedding of weed seeds. Removal of vegetation is common practice in many orchards and nurseries where the wide spacing between rows of woody plants allows for the operation of mowers (Hammermeister, 2016). Mowing also plays a significant role in the control of perennial weeds, for example, *Cirsium arvense* in pastures and whole-year green manure crops (Melander et al., 2016). Repeated aboveground cutting of thistle plants depletes the sugars stored in belowground root structures over time, reducing their potential to infest succeeding crops (Graglia et al., 2006). Finally, the development of intra-row weed control tactics using air-propelled abrasive grit shows promise in crops tolerant to the treatment (Carlson et al., 2018). However, this chapter will not address aspects related to mowing and abrasive grit techniques any further. The main focus is on soil cultivation strategies for the mechanical control of weeds growing in annual field crops sown in narrow rows (cereals, pulses and oilseed crops) or wide rows (sugar beets, maize and many

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http://dx.doi.org/10.19103/AS.2021.0098.11
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vegetables). In this context, MWC is used when the upper 0–5 cm soil layer is cultivated to control weeds. The majority of technologies discussed in this chapter have little effect on the shoots of perennial weeds. Mechanical control of severe perennial infestations requires deeper and more intense cultivations between crop plantings (Melander et al., 2012).

Long before the invention of herbicides, MWC constituted the backbone of weed management. Mouldboard ploughing, seedbed cultivation prior to crop establishment, and inter-row hoeing and weed harrowing within established crops were the primary strategies for reducing weed infestations. However, other preventive and cultural measures were needed to supplement MWC to provide satisfactory control, among which the diversification of crop rotation was arguably most important. In modern times, an increase in conversion to organic farming and the imposition of herbicide restrictions in many European countries and elsewhere around the world have resulted in a revitalization of interest and investment in MWC. Older methods, such as weed harrowing and hoeing, have been the subject of new research to better understand their weeding mechanisms and strategic use in various crops (e.g. Melander et al., 2003; Kurstjens and Kropff, 2001; Rasmussen, 1991). This development began to take off in the 1990s and accelerated in the following years due to further restrictions on herbicide use, increasing problems with herbicide resistance, and poor prospects concerning the development of herbicides with new modes of action (Kudsk and Mathiassen, 2020).

In recent years, the exchange of knowledge and ideas among practitioners, consultants and researchers has increased immensely in countries restricting herbicide use and possessing vibrant organic sectors, such as Germany, Denmark, Austria and Switzerland. This change has led to improvements and many new crop-specific weed management strategies (e.g. Rasmussen et al., 2010; Melander et al., 2018; van der Weide et al., 2008). However, the continuous integration of electronics into mechanical devices for weed control has meant a significant step forward over the last 20 years. Mechanical solutions are now feasible in weed management programmes outside the organic sector. Particularly, the invention of GNSS (global navigation satellite system) and vision guidance technologies has helped automate and ease the task of steering mechanical tools, such as hoes and finger weeders (Machleb et al., 2020). In recent years, implements designed for automatic intra-row weed control in row crops have appeared on the market, and more are likely to come in the future. Intra-row weeds are defined as those growing in the crop line and few centimetres to either side. The prospect that row crops can be grown without herbicides and manual weeding could potentially solve urgent issues, such as herbicide resistance, the absence of effective herbicides, and lack of labour for hand weeding. Growers currently benefit from automatic intra-row weeders in transplanted crops through significant labour savings for manual

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weeding (Lati et al., 2016). In addition, the release of labour for other tasks makes the expansion of acreage with valuable row crops possible, thereby increasing farm income (Melander, 1998). Despite these obvious advantages with new technologies, limitations and drawbacks exist and must be addressed before the broader adoption of MWC can be achieved.

Today's market offers a wide range of weeding devices for the mechanical control of small-sized weeds that can be grouped into three categories: full-width cultivators, inter-row cultivators, and intra-row cultivators (Machleb et al., 2020). Several reviews on MWC methods have been published in recent years (e.g. Gallandt et al., 2018; Machleb et al., 2020; Melander et al., 2005; van der Weide et al., 2008). This chapter will highlight the most recent and relevant advances within each MWC category. The focus will be on novel inventions and developments of mechanical devices, designs, and the weed problems they are meant to solve. Moreover, automation technologies that assist weeding operations are becoming increasingly important and will be given special attention.

2 The mechanisms of mechanical weed control

Weeds that establish from seeds are vulnerable to mechanical control when small in size; they are most sensitive from the white thread stage until the first true leaf begins to unfold. Weeding efficacy declines as weeds develop; however, efficacy decreases at differing rates among weeding devices. The lethal effects of mechanical cultivators arise from the soil disturbance they cause; mechanical cultivation uproots weed plants and covers them with soil, both mechanisms working simultaneously during operation (Melander et al., 2017). Some cultivators also cut weeds, dissecting the roots from shoots or causing damage to the roots, stem, or leaves, contributing to an increased desiccation rate. Uprooting occurs when roots are displaced from their original position, causing them to tear apart. Uprooting reduces root function and increases desiccation rate if soil conditions are dry. Soil burial excludes light and prevents photosynthesis in green plant tissue, becoming lethal if weeds cannot grow through the soil layer due to insufficient energy reserves. Rasmussen (1991) described crop and weeds effects following light tine cultivation, in the form of weed harrowing, by quantifying the amount of soil thrown onto the crop plants. The percentage of crop soil cover provided a reasonable relationship with crop response and weeding effectiveness. However, Rasmussen's studies did not clarify the exact mechanisms responsible for weed mortality when operating a weed harrow. Kurstjens and Kropff (2001) got closer to understanding the mechanisms of tine cultivation using a laboratory weed harrowing setup; this enabled careful assessments of weed size and position and the degree of uprooting and burial damage. Results showed that uprooting is the primary lethal mechanism of tine cultivation when weed seedlings are weakly anchored

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in soil, typical from the white thread stage until the first true leaves start to unfold. Therefore, soil covering becomes an increasingly important mechanism of weed mortality as rooting, and thus anchoring, improves with growth. Even relatively large weeds can be killed through soil burial; however, partial burial increases the likelihood of survival (Merfield et al., 2020). Melander (1997) observed this when covering *Sinapis arvensis* at the zero to two true leaf stage and the two to four leaf stage with 5 cm of soil and achieved approximately 80% and 40% control, respectively. Merfield et al. (2020) suggest that a burial depth of 6 cm will kill most plants regardless of species or growth stage. Weed plants that have surpassed the seedling stage would therefore require cultivation to a greater total soil depth to achieve 6 cm of soil cover. The effects of soil covering described above hold true for tines and weeding devices that provide a ridging action. Notably, hoe shares and other blades possessing a cutting action can uproot or sever weed plants at more advanced growth stages with several true leaves (Melander et al., 2005)

3 Full-width cultivation

Harrowing effectively controls weeds when they are small, before the first true leaves become visible. Post-emergence weed harrowing treats both the crop and weeds uniformly. Therefore, successful harrowing occurs when the increased crop yield attributed to reduced competition from effective weed control is greater than the yield losses resulting from the crop damage and burial inflicted. Selective harrowing typically requires a size difference between the crop and weeds, where crop plants are large enough to withstand uprooting and soil covering, while weed plants are smaller and more vulnerable to mechanical impact (Fig. 1). Several studies have focused on improving the selectivity of full-width weed harrowing in small grain cereals, pulses, maize and vegetables (Melander et al., 2017). The strategic use of weed harrowing and guidelines for appropriate settings during operation have been improved thanks to research and the exchange of knowledge among practitioners. Attempts have been made to adjust the aggressiveness of weed harrowing in real-time according to online weed detection using ultrasonic sensors mounted at the front of the tractor (Rueda-Ayala et al., 2015). Gerhards et al. (2021) determined the intensity of weed harrowing in real-time by computing crop soil cover using digital cameras mounted before and after the harrow. Harrowing intensity was continuously adjusted to achieve 10% crop soil cover; being the pre-set threshold for the decision algorithm, it was expected to maximize weed control efficacy while limiting crop injury. These examples of improving harrowing performance by employing advanced technologies have not yet resulted in the commercialization of equipment, but the potential for improved operation is evident.

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Figure 1 A well-anchored barley crop with few and relatively small weed plants – successful weed harrowing possible. Courtesy of Bo Melander, Aarhus University, Denmark.

As implements, tine harrows have not improved to a noteworthy degree, with the exception of the newly introduced Treffler harrow (www.treffler.net/en/products/agricultural-machinery/precision-tine-harrow, accessed 27 December 2020). The Treffler harrow has not resolved the fundamental problem of low selectivity, that is, treating both crops and weeds. Instead, Treffler has markedly improved the mechanisms for adjusting tine aggression and suspension. Each tine is able to move independently on the frame and is individually preloaded with a spring. Tines can therefore adjust to within-field contours while maintaining constant down-pressure regardless of their position. The Treffler harrow has also demonstrated its advantages for weed harrowing along ridges, such as potato ridges, with the ability to cultivate the plateau-like profile with relative uniformity (Fig. 2). However, following several passes with the harrow, the ridge will have to be re-established.

Ridging potatoes generally offers an excellent opportunity for intense cultivation until the potato shoots start emerging. Potato ridgers, rolling

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Figure 2 Weed harrowing on potato ridges with a Treffler harrow. Courtesy of Bo Melander, Aarhus University, Denmark.

cultivators and weed harrows are all proven effective for weed management in potatoes, but drawbacks have also been encountered. Crop injuries, insufficient working capacities, and forming ridges off centre from crop rows are emphasized among others (Melander et al., 2011). A new invention was introduced recently to resolve some of the problems mentioned called the OptiWeeder (https://msrplanttechnology.dk, accessed 27 December 2020). OptiWeeder does not use modern vision or GNSS technologies to assist the steering task. Instead, units following each row are flexible at their toolbar attachment point, allowing each unit to align independently while following along the ridges. Weed control is achieved by running angled knives on either side of the ridge and on the top that function to undercut weeds at a depth of 2 cm; knives are followed by a set of plates that re-build the ridge. (Fig. 3). Driving speeds of 15 km/h are possible; however, the width of the machine requires further expansion to achieve working rates desired by conventional potato growers. The first tests with OptiWeeder showed high weeding effectiveness and no noteworthy crop injuries, though documentation of its weeding potential is still limited (Fig. 4).

4 Inter-row cultivation

Weed harrowing used to be the principal physical weed control method applied in organic cereals. However, the adoption of weed harrowing in

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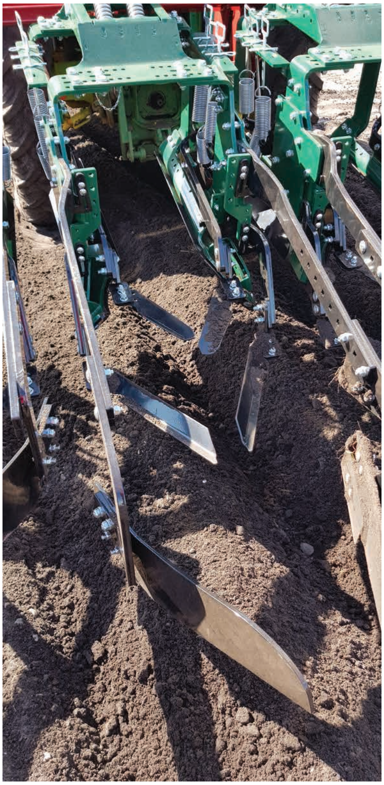

Figure 3 A unit of the OptiWeeder for treating one potato ridge. Courtesy of Bo Melander, Aarhus University, Denmark.

practice has been difficult in many cases. There seems to be a steady move away from the sole use of this technology and towards other methods and strategies. Optimal timing, settings and execution are the main challenges of weed harrowing mentioned by practitioners, leading to poor weed control and occasionally substantial crop yield loss. Erect dicotyledonous weed species with taproots and tall-growing annual grasses are particularly difficult to control; in addition, perennial weed species are not affected much by harrowing (Rasmussen, 1998). Species such as *S. arvensis*, *Brassica rapa* and *Raphanus raphanistrum* are troublesome because they establish quickly, have fast initial growth rates and can emerge in series of cohorts (Rasmussen et al., 2010).

Because of the disadvantages of full-width weed harrowing in cereals and other crops grown at narrow row spacing, growers have turned to inter-row cultivation with steerable hoes. Hoeing between crop rows is widely applied in traditional row crops where the operation is straightforward (Melander et al.,

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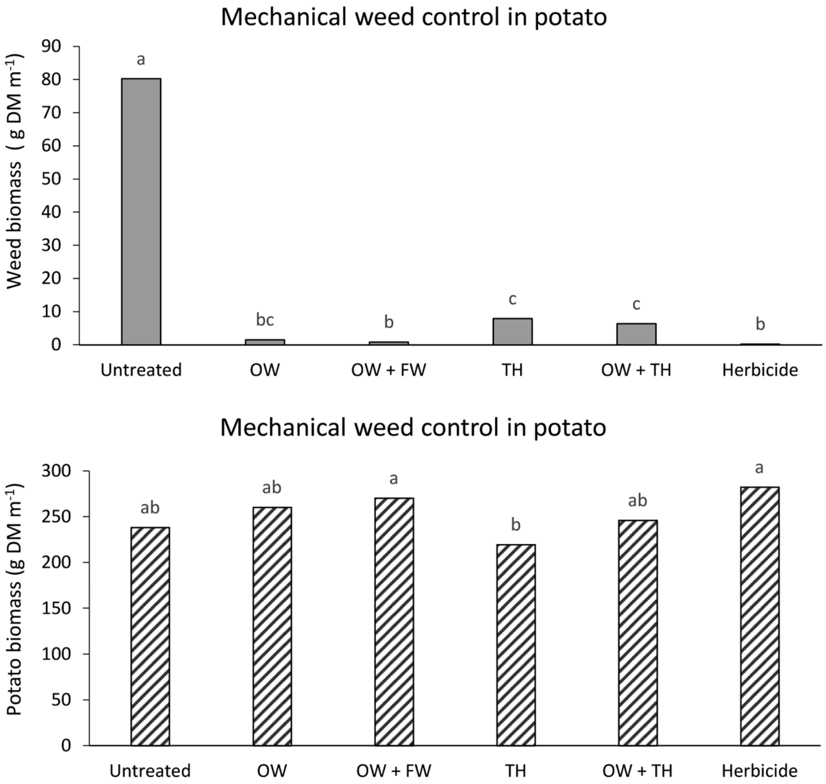

Figure 4 Mechanical weed control in potato with OptiWeeder (O.W.), Treffler harrow (T.H.), and finger weeding (F.W.) – three passes were implemented for each mechanical treatment. Effects are shown for weed and crop biomasses. Columns with similar letters are not statistically different ($P < 0.05$). (Melander, B., unpublished data).

2005; Machleb et al., 2020). The inter-row weeding device typically employed is the goosefoot share, providing a cutting action that nearly removes all inter-row weeds unless soil conditions are wet or weeds have become too large for control (Melander et al., 2005). Inter-row hoeing also has application in cereals grown at an increased inter-row spacing to make room for the operation of a goosefoot share between crop rows (Jabran et al., 2017). Hoeing is most effective against annual weeds but may also have some effect on perennials (Graglia et al., 2006). Belowground propagules are not directly affected by hoeing; however, shoot removal will stimulate re-sprouting, depleting belowground food reserves over time. Shoot removal interrupts the translocation of photosynthetic assimilates to roots and rhizomes; overall, these effects can impede perennial weeds' regenerative capacity.

Renewed interest in inter-row hoeing for cereals and pulses may also be attributed to recent and substantial innovations that ease the task of steering,

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namely, automated systems based on camera and GNSS technologies (Kunz et al., 2018). These technologies remove the need for manual steering and enable inter-row hoeing with greater operational capacity since implement width and driving speed can both be increased (Kunz et al., 2015). Vision-based steering systems typically consist of one or more cameras mounted on the hoeing implement to detect crop lines (Fig. 5). The imaging information is computed to signal actuators that align the hoe with crop rows while driving. Some hoes have a hydraulic side-shift between the hoe and the tractor, enabling the hoe to move right or left; for example, see Garford Robocrop System (https://garford.com/products/robocrop-guided-hoes/, accessed 27 December 2020), which is explained in detail by Connolly (2003). Danish organic growers report that inter-row hoeing in cereals works well with driving speeds of 5–10 km/h and 25 cm inter-row spacing, a doubling of the traditional 12.5 cm inter-row spacing. Manufacturers of vision guidance technologies and hoes claim that inter-row hoeing down to 15 cm inter-row spacing is possible at reasonable forward speeds, but this option is not purchasable yet (Agrointelli, personal communication). Vision guidance technologies are currently dominating the market for automatic steering systems sold alongside well-known hoe brands across Europe (Fernández-Quintanilla et al., 2018). RTK-GPS (real-time kinematic global positioning system) steering systems can also be used for precise inter-row hoeing if the crop rows' positions are recorded during seeding. RTK-GPS does not require crop-specific knowledge but relies on the expected location of the crop rather than real-time information delivered by cameras. However,

Figure 5 Camera-steered inter-row hoeing in spring barley. Courtesy of Bo Melander, Aarhus University, Denmark.

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camera-steered side shifting units can change lateral position instantly and directly in response to the actual conditions in the field, which is a clear advantage over GNSS solutions.

Autonomous tool carriage systems have recently become available on the European market, offering an alternative to automatic tractor-mounted cultivators. Compared to tractor-based MWC, autonomous weeding robots reduce labour requirements and soil compaction; however, they rely on similar methods for tracking and following crop rows. Naïo Technologies (https://www.naio-technologies.com/, accessed 27 December 2020) combines camera-vision and RTK-GPS or sensor-based guidance in their models designed for operation in vineyard and vegetable cropping systems. Agrointelli (https://www.agrointelli.com/robotti/, accessed 27 December 2020) utilizes RTK-GPS and possesses a standard three-point hitch with power take off (PTO). While the designs of Naïo Technologies' and Agrointelli's autonomous weeding robots undoubtedly represent a significant step forward, the tools responsible for weed control remain simple, including selective inter-row tools (shares and knives) and non-selective intra-row tools (finger, torsion, and brush weeders, as well as tine harrows).

Compared to weed harrowing, inter-row hoeing in cereals is more effective against problematic weed species, such as grasses and tap-rooted broadleaved species with an erect growth (Melander et al., 2003, 2018). Moreover, efficacy increases with the proportion of the surface area being cultivated (Fig. 6). Timing of treatment is less crucial with inter-row hoeing than weed harrowing because the shares' cutting action also controls weeds with more than two or three true leaves (Fig. 7). Intra-row weeds are not directly affected by hoe shares

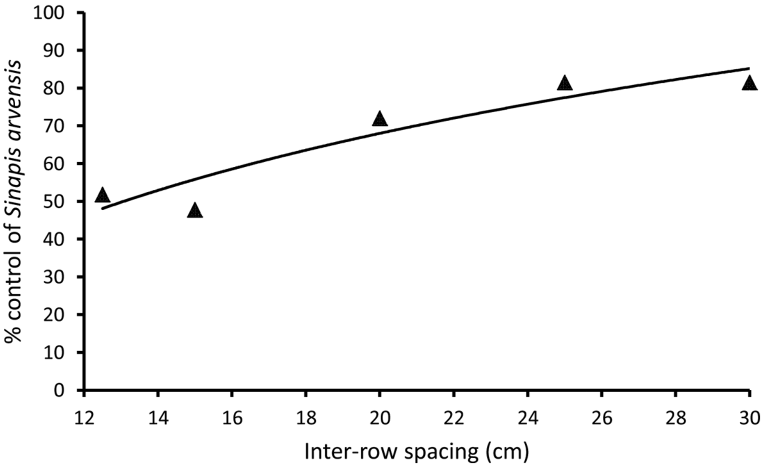

Figure 6 Relationship between % control of *Sinapis arvensis* and inter-row hoeing at increasing inter-row spacing in organic spring barley (Melander, B., unpublished data).

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Figure 7 Effective inter-row hoeing is still possible despite large-sized weeds. Courtesy of Bo Melander, Aarhus University, Denmark.

and are not controlled unless sideways soil movement causes some burial. This ridging action is determined by driving speed and share configuration, and ridging may cause some adverse crop effects if exaggerated (Melander et al., 2018; Wiltshire et al., 2003). Fast driving speed is desirable for the achievement of high work rates but is risky at small crop growth stages when crop leaves are easily buried (Melander et al., 2003). Risk can be alleviated by reducing the share blade angle, making the tool's configuration flatter (Znova et al., 2018). Machleb et al. (2018) observed less sideward soil movement with a flatshare versus the traditional goosefoot share when hoeing in cereals at narrow inter-row spacings of 12.5 cm and 15 cm. Crop yields also tended to be higher with the flatshare, while efficacy was slightly lower than the goosefoot share, which caused more intra-row soil coverage. Flatshares need to work closer to the crop row to achieve similar efficacies as shares with a greater blade angle (Fig. 8). Steering accuracy then becomes particularly crucial with a flatshare to avoid crop injuries. Maintaining a constant and stable position of the shares in relation to the crop rows is another critical factor in ensuring uniform hoeing treatments. Share edges should be kept at the desired distance from the crop row to avoid crop injuries. Apart from accurate steering, the stiffness of shanks onto which the shares are mounted is important to obtain uniformity and reliability. An example of a new shank and share, designed for stiffness and flatness, is shown in Fig. 9.

Intra-row weeds remain a problem when inter-row hoeing, especially tall-growing cruciferous species that can reduce crop yields markedly, as shown in Table 1 (Melander and McCollough, 2020). Mixed intra-row weed populations with a greater proportion of weed species short in stature may not be as competitive as seen in a Danish study with inter-row hoeing, performed in 11 weedy fields

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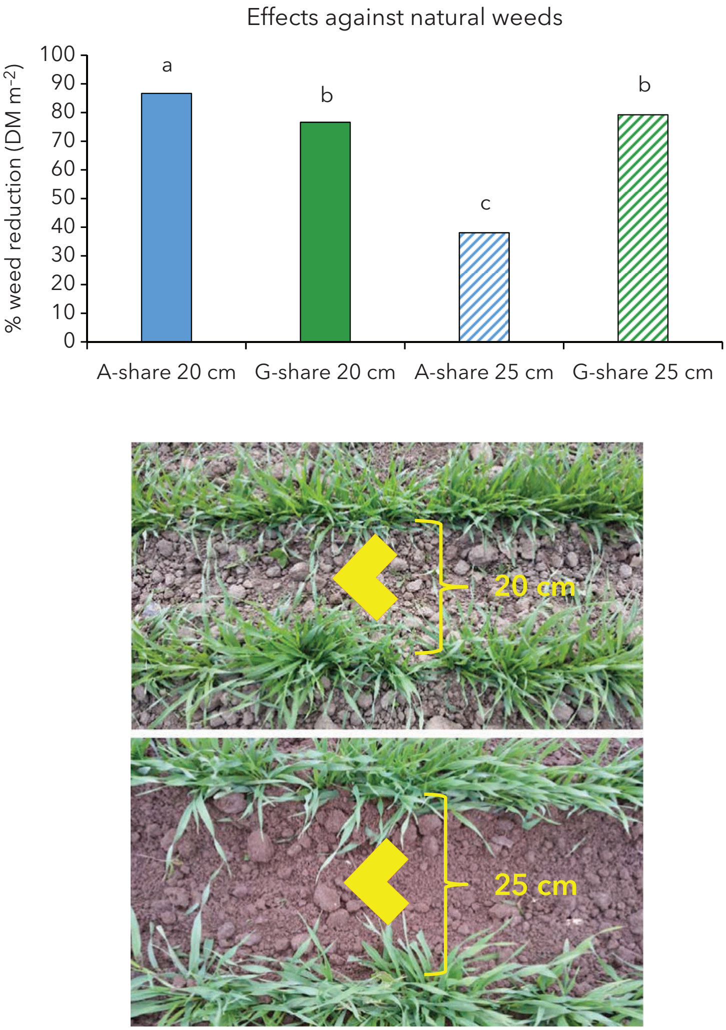

Figure 8 Weeding efficacy of inter-row hoeing in spring barley using a 13 cm wide goosefoot share (G-share) and flat share (A-share, see Figure 9) at 20 cm and 25 cm inter-row spacings. Columns with similar letters are not statistically different ($P < 0.05$). (Melander, B., unpublished data).

with organic spring cereals. Yields were on average only 7% lower with inter-row hoeing versus inter-row hoeing plus hand-weeding of surviving intra-row weeds (Theilgaard and Bertelsen, 2017). Nevertheless, competitive intra-row weeds need to be managed by other means, such as increased weed suppression through band sowing (McCollough et al., 2020a,b) and/or an increase of within-row crop density (Jabran et al., 2017). Supplementary herbicide application or

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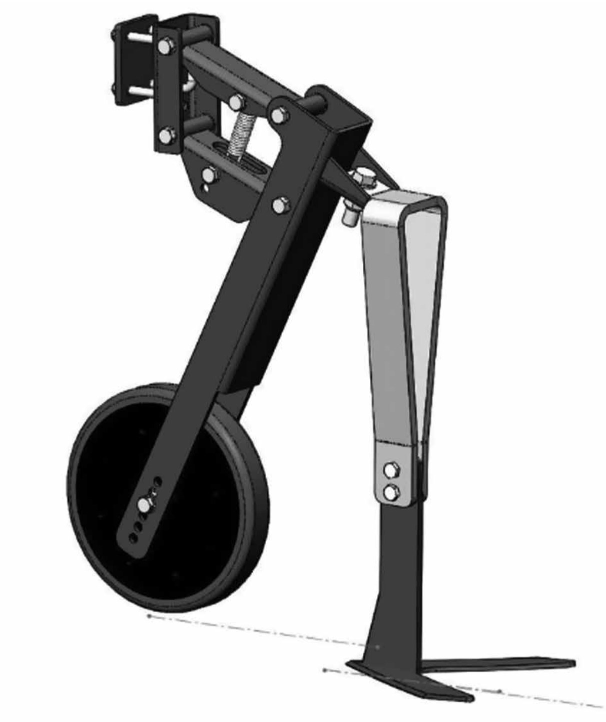

Figure 9 New share and shank design from AgroIntelli (www.AgroIntelli.com, accessed 27 December 2020).

weed harrowing applied pre- and post-crop emergence can reduce intra-row weed numbers and eliminate or mitigate potential yield losses.

Another drawback seen with inter-row hoeing is a yield penalty of 11–12 % in conventional cereals arising from the widening of inter-row spacing from the standard 12.5 cm to 25 cm (Melander et al., 2003). Interestingly, the same yield penalty was not observed in organic spring cereals where wide inter-row spacings (up to 30 cm) yielded the same as narrow spacings (down to 12.5 cm). Lower yields in organically grown crops and the use of manures, from which nutrients are released more slowly and are less abundant, are probable reasons for this discrepancy between the conventional and organic scenarios (Melander et al., 2018).

5 Intra-row cultivation

Crop stands are typically very dense in the intra-row zone of cereals, pulses, oilseed rape and some horticultural crops such as carrot and direct-sown onion and leek. High-density planting makes the selective operation of mechanical

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Table 1 Ranges of yield losses resulting from two years of experiments on intra-row weed competition in organic spring barley and spring wheat, grown at 15 and 25 cm inter-row spacings. White mustard (*Sinapis alba*) was used to simulate cruciferous intra-row weed growth typical for *Raphanus raphanistrum*, *Sinapis arvensis*, and *Brassica rapa*. Intra-row surrogate weeds *Sinapis alba* (plants m^{-2}) are defined as those plants growing in the uncultivated area 2.5 cm to either side of the crop row's center (Melander and McCollough, 2020).

Crop	Intra-row density of *Sinapis alba* Plants m^{-2}	% yield loss
Spring barley	20	12–25
	100	28–70
	500	38–99
Spring wheat	20	13–49
	100	38–86
	500	60–99

tools very difficult, especially if individual crop plants are to be left untouched. Cereal rows can be ridged slightly to control intra-row weeds that are much smaller than crop plants. Any other operation of a mechanical device in the intra-row zones will negatively affect the crop plants, which may result in yield loss. Thus, intra-row weeds cannot be mechanically controlled to a satisfactory degree in densely planted crops.

The operation of mechanical intra-row cultivators such as finger-weeders, torsion weeders, brush weeders become more relevant when within-row crop spacing increases. Finger-weeders steered by automatic guidance systems can be used in many row crops, notably transplanted vegetables (cabbages, onion, leek, celery, etc.). Intra-row cultivators can also be employed in direct-sown row crops when conditions favour effective weed control without crop injuries. This typically happens when there is a marked size-difference between weeds and crop plants, and soil conditions are relatively dry, loose and workable.

5.1 Stacking tools for intra-row cultivation

Intra-row weed control efficacy increases with additional passes and heightening intensity at which each pass is conducted (Melander et al., 2005). Finger weeders and tine-based cultivators work the soil differently; combining or 'stacking' different tools into one pass may improve overall efficacy when compared to single passes with the same tool. Brown and Gallandt (2018) equipped an implement with three intra-row tools in sequence: torsion weeder, finger weeder and tine rake. This three-tool combination resulted in a synergistic effect on surrogate weed mustard (*Sinapis alba*), comparing to treatments using single tools. A range of tool combinations was studied, and not all had a synergistic effect; rather, several were additive. Stacking tools

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also means that the intensity of cultivation increases, and severe crop injuries become more likely since the crop is also treated. The most obvious advantage of stacking tools is that weed problems requiring several intense passes with a single tool might be controlled in one pass when employing the stacking concept. Stacking becomes particularly relevant in well-anchored and robust crop stands that can withstand intense cultivation. Tool stacking may help control weeds in situations where precipitation has delayed field operations, resulting in weeds too large to be effectively controlled with individual tools; however, a favourable outcome is not achieved if the crop is badly injured.

5.2 Automatic intra-row weeding

Intra-row weeds in row crops pose a unique challenge because of their close proximity to the crop. In sugar beet, greater yield reductions result from weeds growing 2 cm from crop plants than from weeds 8 cm away (Heisel et al., 2002). Yield loss caused by intra-row weeds is strongly dependent on the crop species. While intra-row weeds growing within 2 cm of transplanted white cabbage did not reduce marketable yield, intra-row weeds growing the same distance from transplanted onion reduced yield by 60 % (Fig. 10) (Melander et al., 2015). For most row crops, automatic intra-row weeding machines must operate as close to the crop plants as possible to minimize yield loss and the need for manual removal of surviving weeds (Lati et al., 2016; Fennimore et al., 2014). As weeds are most vulnerable when small in size, the same is true for the establishing

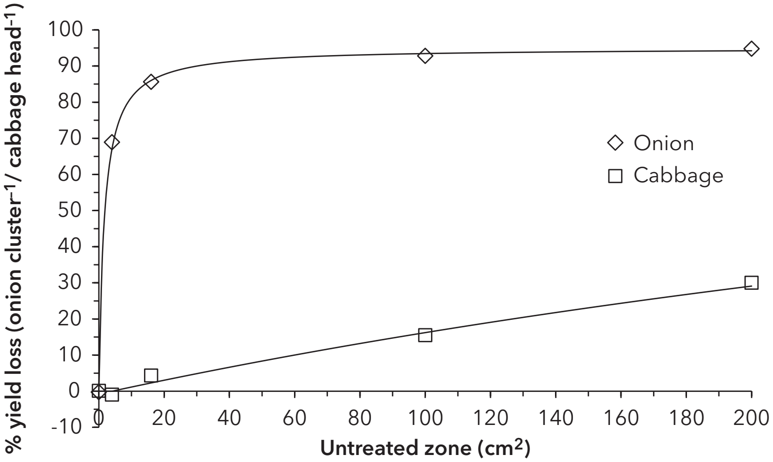

Figure 10 Percent weight loss per onion cluster and per cabbage head as affected by the size of a non-weeded zone around the crop plant (Melander et al., 2015, with permission from Crop Protection).

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crop. Balancing the efficacy of weeding near crop plants while minimizing crop injury is another important consideration; selectivity must be considered while implementing automated post-emergence treatments.

In transplanted crops, automated intra-row weeders outfitted with vision-guidance systems are capable of cultivating between crop plants within the row without reducing crop stands or yields (Lati et al., 2016). Currently, five automatic intra-row weeders are available for practical use in the European market: Robovator (www.visionweeding.com, accessed 27 December 2020), Robocrop InRow (www.garford.com, accessed 27 December 2020), Steketee IC (www. steketee.com, accessed 27 December 2020), Ferrari Removeed (www.ferraricostruzioni.com, accessed 27 December 2020) and Farmdroid (www.farmdroid.dk/en, accessed 27 December 2020). The Ferrari Removeed uses infrared light sensors to detect crop plants, while Robovator, Robocrop, and Steketee IC-weeder use cameras to detect crop plants, distinguishing them from weeds. The website mentioned for each weeder contains excellent images and video clips that visualize the working principles of these intelligent cultivators.

The Robovator consists of a pair of rigid tines, each equipped with a flat knife-like blade that operates horizontally to the soil's surface at a depth of 1–2 cm, removing weeds by cutting (Fig. 11). Additional hoe shares treat the inter-row zone on either side of the crop row. Automated blades function in the intra-row zone until they approach a crop plant. At that point, the computer settings determine when to move the blades apart to avoid crop injury. When the crop plant has passed, the blades close and continue cultivating the intra-row. The movement in and out of the crop row is performed by a hydraulic actuator that responds to information produced by a camera mounted directly in front of it (Fig. 11). For each crop row, there is a camera that detects every crop plant based on the size differential between crop and weeds. Images are processed by a computer that calculates when the actuator must be activated according to driving speed and proximity to crop plants. The Steketee IC-weeder also has cameras that detect crop plants

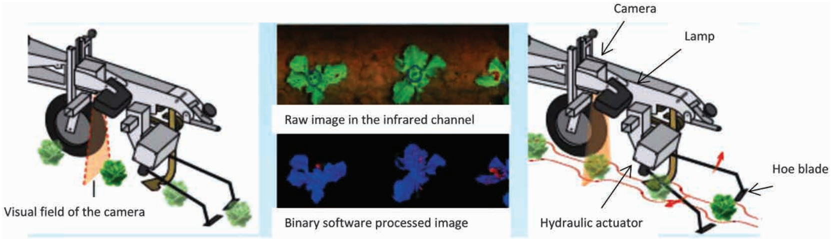

Figure 11 The working principles of the Robovator, intelligent mechanical intra-row weeder (Melander et al., 2015, with permission from Crop Protection and Enginøren).

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to provide visual information for computation. The subsequent guidance of a mechanical weeding device selectively controls for intra-row weeds. The device consists of a pair of sickle-shaped knives that move in and out of the crop row by pneumatic pressure created from a compressor. In contrast, the Robocrop InRow weeder employs a crescent-shaped disc that rotates about an axis. The tool is set to cultivate at a shallow depth of 1 cm to 2 cm within the crop row. The crescent-shaped disc is designed to arc around crop plants, cutting between the plants as it rotates. Rotation of the disc is synchronized with forward movement and informed by crop plant positional information delivered from the imaging camera. The disc is coupled directly to a hydraulic motor, driven by a proportional hydraulic valve controlled by the Robocrop computer.

The Farmdroid is an entirely different concept based on GNSS technology for marking a single crop plant's position. The machine is designed to perform both crop sowing and mechanical intra-row weeding. The placement of every crop seed is recorded during sowing; this geographical information is used to guide knife-like blades, weeding around the area where the crop plants are expected to establish. The blades move in and out of the intra-row zone, similar to Steketee and Robovator. In contrast to machines based on canopy monitoring, intra-row weeding can begin before crop emergence. The futuristic

Figure 12 Farmdroid working in newly established winter oilseed rape. The oilseed rape was sown by Farmdroid and is now being inter-row cultivated – another possible application with the machine. Courtesy of Sven Hermansen, SEGES, Denmark.

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design of Farmdroid becomes apparent by its unmanned autonomous operation, powered by solar panels charging four batteries (Fig. 12). Currently, Farmdroid is the only machine that offers a selective autonomous intra-row weeding solution for direct-sown crops.

5.3 Experiences with automatic intra-row weed control

All the vision-guided machines mentioned above are best suited for use in crop stands where a clear crop-weed distinction is present. Crop recognition, and thus weeding accuracy, becomes more precise and reliable when crop plants are distinctly larger than the weeds and when there is abundant spacing between crop plants within the row (Frank Poulsen Engineering, personal communication).

There are relatively few scientific evaluations of the weeding performance of new automatic weeders. One study evaluating the performance of Robocrop in transplanted cabbage showed that under normal commercial growing conditions, crop damage levels are low, with weed reductions in the range of 62–87%, measured within a 24 cm radius zone around treated crop plants (Tillett et al., 2008). Fennimore et al. (2014) compared the performance of Robocrop with a standard inter-row cultivator in transplanted vegetables. As expected, intelligent weeding was more effective than the standard cultivator at reducing intra-row weed density and subsequent hand weeding times; this was mainly because the standard inter-row cultivator could not remove intra-row weeds. Lati et al. (2016) also compared automatic intra-row weeding using Robovator to a standard inter-row cultivator without the ability to control intra-row weeds in transplanted lettuce and direct-seeded broccoli. Despite the standard cultivator only leaving a 10.2 cm wide non-cultivated band centred over the crop line, automatic weeding was superior when weed pressure was moderate to high. The Robovator removed between 18% and 41% more intra-row weeds, resulting in up to 45% saving of hand-weeding labour compared to the standard cultivator. However, Robovator was not superior to non-intelligent intra-row weeding tools, such as the finger-weeder, weed harrow, and torsion weeder when operating in transplanted onion and white cabbage (Melander et al., 2015). Robovator removed between 54% and 86% of intra-row weeds, and only minor differences in efficacy were found among intelligent and non-intelligent cultivation treatments. Robovator works around a 'safety zone' encompassing the base of each crop plant, within which the decision algorithm prevents any hoeing from taking place to avoid crop injuries. In Melander et al. (2015), uncultivated safety zones of 4 cm and 6 cm were tested; however, zone size was found to have negligible effects. Tools without intelligence cultivate the entire area around crop stems, therefore, damaging crop plants. Theoretically, intelligent weeding should result in lower

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intra-row weed control than non-intelligent tools, but there are no indications of that. The weeding mechanism of Robovator is more about cutting (and partly uprooting) the weeds rather than covering them with soil, typical of the tine-based weed harrow and the finger-weeder. The effect of cutting weeds rather than burying them is more aggressive and less sensitive to weed growth stage at the time of treatment (Jones et al., 1996). Robovator may also be used later than most non-intelligent tools, allowing more weeds to germinate before cultivation and resulting in more weeds being controlled than with earlier treatments. Although the Robovator cultivates a smaller percentage of the intra-row area than the non-intelligent tools, Robovator's improved weeding efficacy may offset assumed adverse effects. As emphasized in Melander et al. (2015) and Lati et al. (2016), intelligent weeding has many other benefits over non-intelligent tools, including increased hours of operation (which is possible at night), ease of implementation, reduced risk of crop injury, need of only one operator, greater flexibility in treatment timing in relation to weed growth stage, and being the only alternative to manual intra-row hand weeding in lettuce.

The performance of Farmdroid has not yet been documented; however, some experiences have been garnered from operating units in commercial sugar beet fields over the last 2 years (Hermansen, 2020; personal communications with project manager Otto Nielsen at Nordic Beet Research (https://www.nordicbeet.nu/en/, accessed 27 December 2020) and farm manager Tom Ellerød Hansen at Oremandsgaard, Denmark). Farmdroid runs at a forward speed of only 0.8 km/h, weeding six rows simultaneously, resulting in low work rates. However, the machine can operate 24 h a day due to continuous battery charging during the daytime hours via attached solar panels. The crop seed-mapping feature makes intra-row weeding possible shortly after crop sowing and onwards, thanks to its autonomous operation. Large areas may require the simultaneous operation of several units, increasing investment costs markedly. Similar to camera-based intra-row weeders, the proximity at which knife-like blades can operate relative to crop plants without injury has a significant influence on the success of weed control. Fields with low weed pressure will have fewer weeds establish in the uncultivated safety zone around crop plants; whereas, fields with high weed pressure will inevitably have more survivors, requiring subsequent treatment measures, such as hand-weeding, to achieve satisfactory control. Practitioners have reported that the slow forward speed employed during crop sowing results in reliable positioning of the emerged crop plants. This enables intra-weeding as close as 1 cm from each plant's centre, especially if crop rows are treated from both directions; the knife-like blades are adjusted to weed closer to the crop plant upon passing. Therefore, the weeding action is performed in a movement away from, rather than towards, the crop plant.

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One pass from each direction is needed to treat one row from both sides. The period in which effective weeding can take place is quite broad since the cutting action of tools can control weeds beyond the cotyledon stage. More importantly, Farmdroid can operate continuously, preventing weeds from becoming particularly large. Intra-row weeding machines reliant upon GNSS references do have the disadvantage of not cultivating areas where a seed has been planted, but a crop plant failed to establish, whereas camera-guided implements avoid all established crop plants and treating everything else.

The Farmdroid and the camera-guided solutions all undergo continuous improvement, receiving both hardware and software upgrades as these technologies continue to evolve. Changes to construction and design are also made; for example, the first version of Farmdroid was very light, which limited its function on heavy soils. Such experiences from the field have necessitated a heavier version with more robust components, including the frame, toolbar, shanks, weeding devices and wheels. Thus, the performance of an automatic intra-row weeder observed in one growing season may not hold true in the next due to continuous upgrades.

5.4 Perspectives for automatic intra-row weeding in direct-sown row crops

Industry representatives, advisory bodies and the research community all agree that the adaption of intelligent intra-row weeding technologies for operation in direct-sown row crops would constitute a major step forward (Utstumo et al., 2018; Melander et al., 2015). With seeding and weeding capabilities integrated into the same machine, Farmdroid is the only on-market implement specifically designed for operating in direct-sown crops. Sole reliance on GNSS technology for crop plant detection may be upgraded in the future and supplemented by vision guidance, helping to solve the problem of missing crop plants within the row and enhancing crop detection in general.

By using artificial intelligence and machine learning, significant progress is being made in developing vision-based technologies for selective intra-row weeding in direct-sown row crops. Machine learning is an iterative process; when the model does not detect crop plants accurately, previous images are re-assessed, and the model is revised to handle new data with greater accuracy (Fig. 13). Detection models are continuously rebuilt to handle crop plants' varying in appearance among different sites and growth stages. Eventually, comprehensive training across many scenarios will lead to a reliable crop detection system. Robovator is currently capable of adequate intra-row weeding in direct-seeded sugar beet fields with weeds overlapping the crop plants

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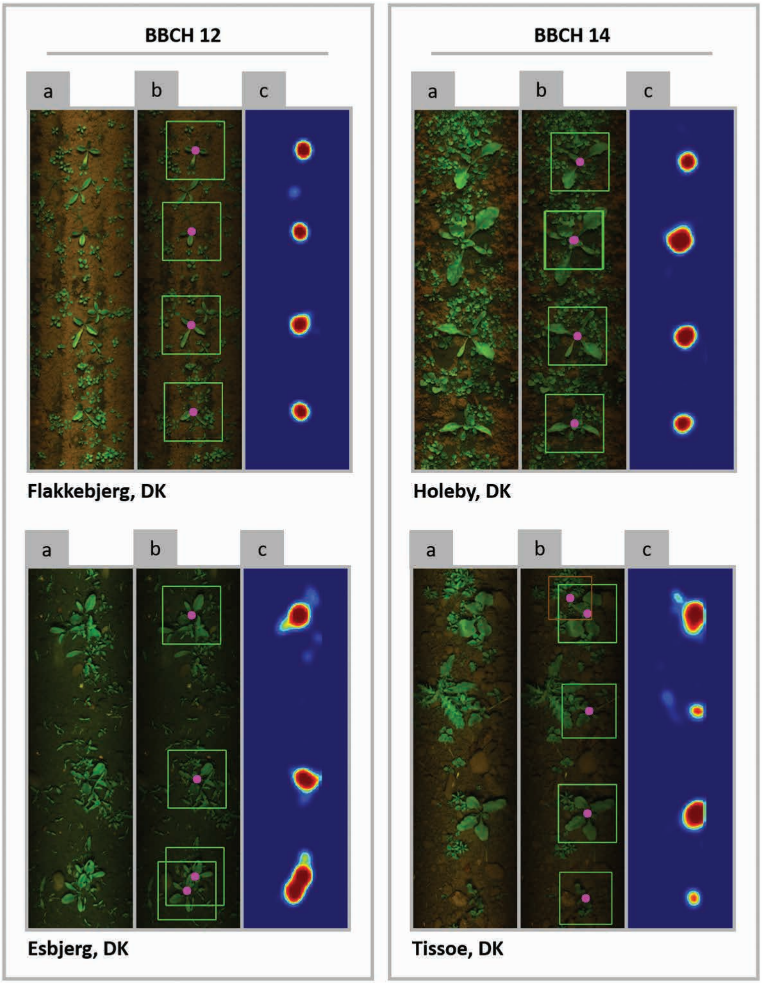

Figure 13 The ability of artificial intelligence (A.I.) to identify young direct-sown sugar beet plants in multiple varying scenarios. Examples include instances where weed pressure can be characterized as moderate to heavy. Successful crop detection is depicted across four sites in Denmark and at two early crop growth stages; the two true leaf stage (BBCH 12, left) and the four true leaf stage (BBCH 14, right). Images show (a) the raw image captured by the camera, (b) an A.I. output pinpointing the centre of each detected sugar beet plant, and (c) a second A.I. output depicting a heat map, showing the probability of sugar beet plant presence. Courtesy of Frank Poulsen Engineering.

(Fig. 14). Steketee IC has also taken on the challenge of achieving precise and reliable crop recognition in direct-seeded sugar beet, however, their current minimum requirement of 21 cm within-row spacing makes it difficult to achieve desired crop densities per hectare.

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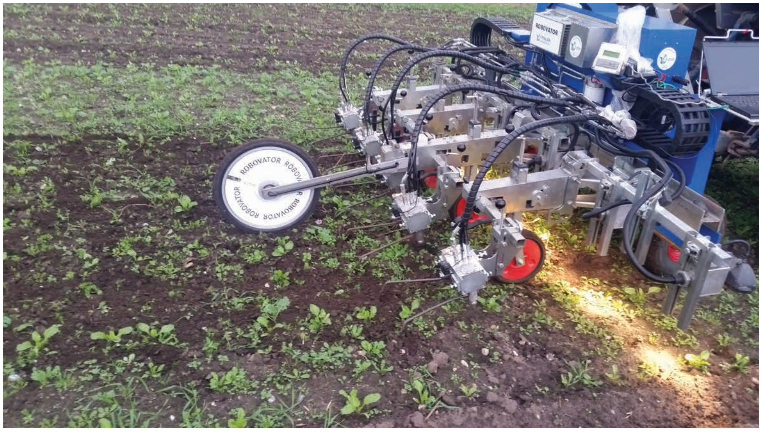

Figure 14 Robovator operating in weedy sugar beets. Courtesy of Frank Poulsen Engineering.

6 Future trends and conclusion

Full-width cultivation suffers from the fact that crops and weeds are treated simultaneously. New implements have emerged in recent years, and knowledge about the operation of full-width cultivators is continuously improving. Equipment design and the ease of making adjustments are also progressing; it is impressive to watch skilled growers operating these tools and the effects they can achieve with them. Nevertheless, the fundamental problem of non-selective implements remains a barrier for broader application and popularity; this issue is unsolvable as long as tools do not discriminate crop plants from weeds.

The increasing interest in inter-row cultivators does not stem from an ambition to solve the intra-row weed problem. Instead, the aim is to simplify and improve the control of inter-row weeds directly affected by the weeding device. Automatic steering systems constitute a major step forward in this regard, but the refinement of tools is still pertinent. The concept of stacking tools is an option with most commercial inter-row cultivators, although the solutions are often a compromise between cost and necessity. Inexpensive solutions comprised of inter-row tines mounted behind shares are often seen; however, the addition of tines may only contribute limited effects to work already done by aggressive shares. Given soil conditions prone to aggregate formation, hoeing efficacy may be diminished due to the survival of weeds attached to soil clods following cultivation. Weeds that remain upright and whose roots are protected from desiccation are likely to survive in a clod of soil if soil moisture remains adequate (Fig. 15). Mounting a device with a rotating and crushing action behind hoe shares is an appealing idea for breaking apart clods, resulting in weed roots' exposure. The split-hoe demonstrates such a

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Figure 15 Weed seedlings attached to a clod. Courtesy of Bo Melander, Aarhus University, Denmark.

feature; however, the current iteration of the machine is designed for high-value specialty crops only (Pannacci et al., 2017).

Intra-row weeds remaining in the hoed cereal system pose a problem for the preservation of crop yields. The within-row crop stand is too dense for the operation of intelligent in-row weeding devices without inflicting crop injury. Preventive and cultural strategies, as well as the inclusion of tine harrowing, can provide some additional control of intra-row weeds; however, some weed species may escape these measures and reduce crop yields. Organic growers usually accept surviving weeds after mechanical interventions. Conventional growers expect cleaner fields; weedy crop lines may hinder the broader acceptance of the hoed cereal system. Other considerations, such as work rate and investment costs, may impede adoption among conventional growers. Band-spraying may be a viable solution to the intra-row weed problem. Preliminary results from the United Kingdom suggest that compared to full-width spraying, a 60% reduction in herbicide use is achievable when band spraying in cereals grown at a 16 cm row spacing (Cussans, J., personal communication). Results are undoubtedly in line with EU policies on integrated pest management, but feasibility relies on the practicalities of integrating band-spraying with inter-row cultivation.

Significant progress has been made in recent years regarding intelligent intra-row weeding in row crops that leave enough space for the selective operation of a weeding tool. Both vision and GNSS technologies are continuously being improved for plant detection, and automated weeding

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technologies are expected to become more affordable over time. Georeferencing technology may soon lead to the establishment of crops in a grid-like arrangement, with even spacing between individual plants (Machleb et al., 2020). The GeoSeed by Kverneland (2020, https://be.kverneland.com/Actualites/Product-news/Archive-2015/Electric-drive-GEOSEED-offers-new-opportunities, accessed 23 July 2021) aims to sow crops in a pattern that allows for crosswise inter-row hoeing in opposing directions. If successful, this might lead to selective and crosswise weed harrowing in cereals established within a grid. However, seeding technology requires further improvement before precision planting becomes possible. A challenge shared by the developers of vision- and GNSS-based crop and weed detection systems is improving accuracy, so automated selective intra-row cultivation can be implemented in closer proximity to crop plants. By minimizing the uncultivated ‘safety zone’ surrounding individual crop plants, remaining intra-row weeds may be reduced to densities of insignificant concern; indeed, this scenario is already a reality in some transplanted row crops (Melander et al., 2015). To apply automated precision weeding in direct-sown crops, several issues must be addressed in the future. For example, the trade-off that exists when reducing operation distance between weeding tool and crop, between the crop injuries resulting from physical disturbance, and the yield benefits associated with weeding a greater area of the soil’s surface. As automatic intra-row weeders are developed to function in direct-sown crops, it is essential to parameterize the crop-related effects of mechanical and thermal weeding devices across early growth stages, at multiple intensities, and multiple working distances from crop; such research is currently underway in Denmark. The benefits of MWC in close proximity to crop plants are obvious for the organic sector, as well as conventional specialty crops lacking effective herbicides (Fennimore et al., 2014). For conventional row crops where effective herbicides are still available, spot-spraying of close-to-crop weeds in combination with intelligent intra-row weeding could minimize herbicide consumption immensely and live up to the intentions of IPM.

7 Where to look for further information

The following chapters in textbooks provide useful introductions to the subject:

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E. Hatcher & R. Froud-Williams). John Wiley & Sons Ltd, West Sussex (U.K.), 245-270.

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Important research on mechanical weed control is currently conducted in the ongoing EU Horizon2020 project with the acronym IWMPRAISE grant agreement No 727321 (https://iwmpraise.eu/).

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