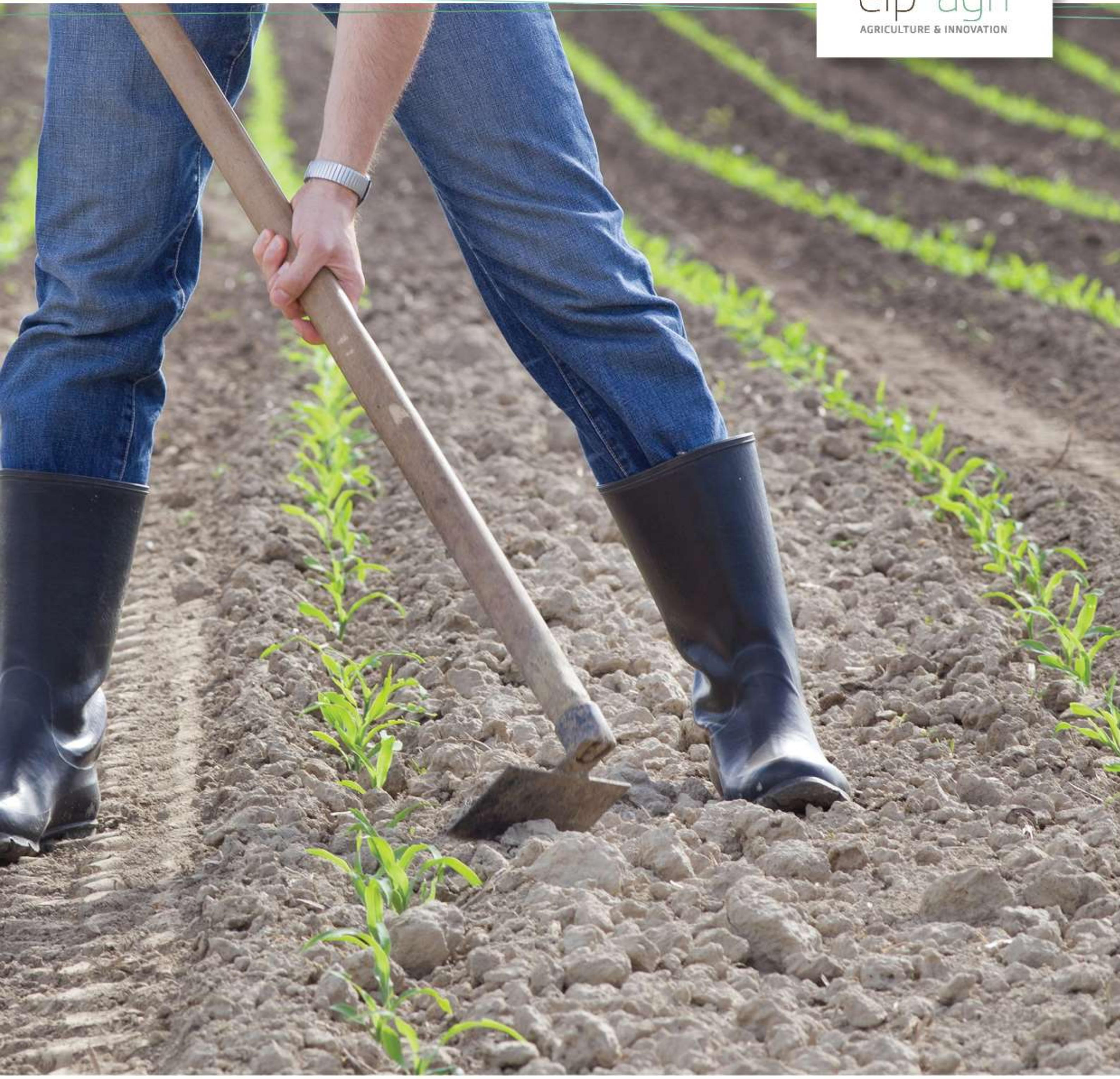
EIP-AGRI Focus Group
Non-chemical weed management in arable cropping systems



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A vision for the opportunities for precision non-chemical weed management in 2050 and beyond

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Abstract: Precision weed management is improving through mapping and guidance systems. However, there are several obstacles for wide scale adoption, many of which involve the challenge of getting really close to remove weeds near the crop being grown. The paper shall describe the precise implementation of implements for mechanical weed management for narrow and wide spaced crops and mechanisms that are required for successful adoption in the front and/or rear attachment location of an agricultural used vehicle. In addition, the technical and structural requirements for high-precise application will be described, as well as the opportunities, options and uses of weed mapping. Where applicable the challenges of encouraging adoption of such methods are discussed.

Introduction

Agricultural operations are becoming increasingly more precise as technological developments enable improved data collection. Many start-up companies are developing in this fast moving sector to fill the gap in the market for hard and software to enable improved observations, recognition, images, collection, analysis and eventually treatment of weeds. Improvements in weed control are being developed for both chemical and non-chemical applications and these operate differing scales of precision. As chemical weed control options reduce due to legislation, environmental concerns, chemical resistance and supplier chain demands, non-chemical options need to be developed to order farming systems to work effectively. For some crops these are already developed and are becoming standard management practice but other crops and situations are far more challenging to address. It is also recognized that non-chemical weed control can raise both environmental and economic concerns and so factors influencing adoption of non-chemical weed control by the farming community need to be acknowledged and addressed. This paper will discuss some of these challenges and opportunities for non-chemical weed control currently being developed and possibilities for future control.

Scale of precision available in 2019

	Chemical options	**Non-chemical options**
Farm	Easily achieved	Easily achieved

Field	The normal management however now facing challenges of chemical resistance, product withdrawal and environmental pressures.	Used on organic farms or where product specification or challenges in chemical control lead to predominately-mechanical removal techniques.
Site specific	Achievable through either satellite, drone, manual scouting mapping and zoned spray applications.	Achievable through either satellite, drone, manual scouting mapping and then selective use of machinery which is generally restricted to machinery width.
Plant specific	A range of systems are under development but few are commercially available.	Currently predominately achieved through point treatment but mainly through hand weeding.
Leaf specific	Under development but not available commercially	None available

Mechanical weeding in narrow-spaced crops

Narrow-spaced crops are those established at high seed rates and small distances between crop plants within the row. Cereals, rapeseed, beans, peas etc. are the most common agricultural crops grown in narrow rows. These crops are normally grown in crop stands with a row distance of around 12 cm. Such a small distance challenges mechanical weed control. Weed harrowing is today's principal method other than from crop competition. The effect of weed harrowing mainly arises from soil coverage and uprooting of weed plants, and selective conduction depends on a size difference between crop and weed plants; the crop needs to be larger and more firmly anchored than the weeds (e.g. Rasmussen et al., 2009). Thus, weed harrowing is extremely dependent on timing and treatments are most effective before weed seedlings start to develop true leaves. Weed harrowing can be done at high work rates using 12 m working widths and driving speeds up to 12 km h^{-1}

When row spaces increase to 20 cm then inter-row hoeing with automatic steering systems is a growing weeding technique in narrow-spaced crops. Hoeing is more aggressive than weed harrowing, and especially tap rooted weed species are more efficiently controlled by hoe blades (Melander & Jørgensen, 2003). Steering is accomplished with cameras and/or GPS-systems that allow the hoe blades to operate close to the crop plants without damaging them. In cropping systems based on inter-row hoeing, the crucial question is which inter-row distance to use. Several investigations around optimal row distance in different crops have been done (Melander et al., 2005). Pedersen (2000) showed that in winter wheat 24 cm row distance gives the same yield as 12 cm if the seed rate is maintained when going from 12 cm to 24 cm. Boström et al (2012) achieved lower yields in most crops when increasing the row distance beyond 12 cm while Melander et al. (2018) found no yield penalties associated with inter-row spacings up to 30 cm in organic spring cereals. A fixed trial over 5 years with different organic crops (cereals, field bean and grass seed) gave greater yields in 4 out of 6 years using inter-row hoeing at 25 cm row spacing as compared with 12,5 cm and weed harrowing (Ståhl et al., 2011). At 50 cm row spacing, however, the yield was 10-13 % lower than at 25 cm in ten field trials with spring wheat and winter wheat Sweden (Ståhl et al, 2016). In conventionally grown winter oilseed rape, no yield reductions were seen going from 12 cm inter-row spacing and up to 48 cm in 16 trials, 2003-2007 (Nilsson 2007). Melander et al. (2018)

stated that conventionally grown cereals at high yield levels seem to be more sensitive to increased row spacings than organic cereals, probably due to differences in fertilization and other inputs.

The weed pressure has a big influence in the yield response following inter-row hoeing. Under weed-free conditions, the narrowest row spacing in general results in the greatest yield (Fahad et al., 2015,). Field trials in organic spring cereals with inter-row hoeing at 25 cm row spacing in Denmark showed that when > 20 % weed cover (in untreated plots) was present at heading, hoeing provided an yield increase (Bertelsen, 2016).

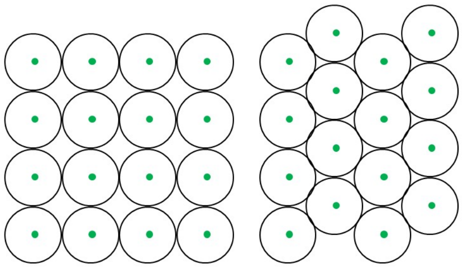
The crop competition is also important in hoed cropping systems for the suppression of weeds in the row; those that are not directly impacted by the hoe blades. Spring tines and finger wheels working in the row are used in row crops, such as maize and rape seed, but are more difficult to apply in crops having dense stands in the row. At present, suppression from the crop seems to be the only option for minimizing the importance of intra-row weeds. Recent studies have shown that widening the row (band sowing) can improve the suppression of intra-row weeds as compared with sowing in lines (Olsen et al., 2005, 2006 and Weiner et al, 2001). The wider the row distance the more important it is to widen the intra-row space also. In organically grown spring wheat, a 7 cm band width gave 4 % greater yield at 25 cm row spacing than normal band width (2 cm) (Ståhl et al., 2018). At 50 cm row distance in organically grown spring wheat and winter wheat, a 12 cm wide band gave 6 % greater yield compared with normal 2 cm wide rows and 50 cm inter-row spacing (Ståhl et al., 2016). However, the optimal band width at a certain row spacing needs further investigation in different crops both in terms of yield responses and weed suppression of intra-row weeds.

Cutting the weed in the crop with knifes is another option to influence weed growth. It has been tested in pots and in field trials (Lundkvist et al, 2011). The knifes can cut weeds with a stem that is thicker than the leaves of the crop. The technique was tested on farms at wide crop row spacing but the denser the crop in the row, the more difficult the selection of weeds from the crop.

The conditions for crop production vary a lot in different regions in Northern Europe. To be able to benefit from banded rows and inter-row hoeing to its full potential, it is essential to have the right conditions in place. Farm layout and the amount of stones in the soil are two important factors. With good conditions in place, inter-row hoeing is a straightforward method to apply.

Are there alternative options for weed control within the rows of narrowed-spaced crops? Could it be possible to place the seeds in a grid-like pattern that would make it possible to do intra-row mechanical weeding? Other options might be relevant but more research is needed.

Figure 1 Proposed spatial distribution of plants in narrow row spaces to enable intra row weeder in narrow spaced crops



Robot-assisted intra-row weeding in row crops

Intra-row weeds in row crops pose unique challenges due to their proximity to the crop. For example in sugar beet, greater yield reductions result from weeds growing 2 cm away from the center of crop plants than from weeds established 8 cm away (Heisel et al. 2002). Yield loss caused by intra-row weeds is also strongly dependent on the crop species. While intra-row weeds growing within 2 cm from the stems of transplanted white cabbage plants did not reduce marketable yield, intra-row weeds growing at the same distance from transplanted onion plants, reduced yield by 60 % (Melander et al., 2015). For most row crops, it is essential that robotic intra-row weeding machines are able to operate as close to the crop plants as possible to minimize yield loss and the need to remove any surviving weeds by hand (Lati et al. 2016; Fennimore et al. 2014). Mechanical and thermal weeding devices are most effective when the weeds are small and juvenile; efficacy declines as weeds become larger and better established (Lundkvist 2009; Ulloa et al. 2010). While weeds are most vulnerable when small in size, the same is equally true for the establishing crop. Balancing efficacy of weeding while minimizing crop injury is, therefore, another important consideration, and selectivity of weed management tactics must be considered while implementing direct, post-emergence treatments.

In a transplanted crop, robotic weeders fitted 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, four such weeders are available for practical use on the European market: *Robovator* (www.visionweeding.com), *Robocrop* (www.garford.com), *Steketee IC* (www. steketee.com) and *Ferrari Remoweed* (www.ferraricostruzioni.com). The *Ferrari Remoweed* is very new to the market and uses infrared light sensors to detect crop plants, while the other three machines detect crop plants using cameras. All of the 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 accurate and reliable when crop plants are distinctly larger than the weeds (Frank Poulsen, personal communication), and when there is enough space between crop plants within the row to operate a weeding tool.

There are very few scientifically-based evaluations of the weeding performance of the new robotic 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 240 mm radius zone around crop plants (Tillett et al., 2008). Fennimore et al. (2014) compared *Robocrop* with a standard inter-row cultivator in transplanted vegetables and, as was expected, they found intelligent weeding more effective than the standard cultivator at reducing intra-row weed numbers and hand weeding times; this was mainly because the standard inter-row cultivator could not remove intra-row weeds. *Robovator* was not superior to non-intelligent intra-row weeding tools in a study performed in transplanted onion and white cabbage; only minor differences in efficacy were found, which could be attributed to the settings of the simpler implements (Melander et al., 2015). Still, intelligent weeding has many benefits over the non-intelligent tools, such as more hours of operation (operation is even possible at night time), easier to implement in practice, less risk of crop injury, only one operator is needed, more flexibility in treatment timing in relation to weed growth stage, and it is the only alternative to removing weeds by hand in lettuce (Melander et al., 2015). There is a general consensus in the industry, advisory bodies and the research community that the adaptation of intelligent intra-row weeding technologies to operate in direct-sown row crops and not just in transplanted ones, would constitute a major step forward (Utstumo et al. 2018; Melander et al. 2015). However, several issues need to be resolved. For example, there is a trade-off between reducing the operational distance between the weeding tool and the crop and the yield benefits associated with weeding a greater area of the soil's surface. As robotic hoes and flame weeders are developed to function in direct-sown crops, it will be essential to quantify their efficacy and the likely damage to the crop at different growth stages, for different frequencies of weeding, and at different working distances from the crop plants.

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Precision tractor and implement implementation

Mechanical weeding needs very precise steering of the tractor and actuation of implements as well. This operation is precise in low-speed operations and restricted in performance due to width-restricted hoeing implements (Bowman, 1997). The speed during mechanical weeding takes place between 2-10 km h^{-1} using mechanical, hydraulic, and electric actuators on the implement operated either by a second person or by the driver (Griepentrog et al., 2007). New developments include camera-based systems, which allow a fully automated steering of the implement. Another important influence on the performance of mechanical weeding is the accuracy of crop positioning, which is very imprecise for most trailed seed drills and planters due to movement through the hitch point leading to some movement within the croprow. With the introduction of machine guidance systems and of precision drilling into a well-prepared seedbed, the crop architecture and plant spacings within and between rows can be very precisely controlled in extremely straight rows.

Economics and the ease of using chemical herbicides is often preferred by growers compared to mechanical solutions. Tractor-mounted implements for weed management have, therefore, disappeared almost completely except in high value crops or organic farming. Chemical crop protection is, however, under more and more socio-environmental and scientific pressure. In particular, the political force towards organic farming leads to a new focus on mechanical weed management solutions, which are able to compete financially with the use of herbicides. This requires new technical solutions on both tractors and implements.

Implementation of Implements

In principle, implements can be attached to a tractor in three different ways, such as trailed, semi-mounted, and mounted. All variants show a degree of freedom for the implement to move “unexpectedly” in lateral and horizontal directions. Movement for trailed implements is greatest and least for attached/ounted implements. Mounted versions can be stabilized through special blocks between the lower links of the three-point hitch and the frame of the tractor, which prevent any direct movement in horizontal directions when lowered to the working position, but the whole tractor-implement system can still move to a horizontally off-targeted position while working. Semi-mounted and trailed implements with fixed mounted axles/wheels can move horizontally for various reasons such as the slope of the field, differences in soil resistance on different sections of the implement, and incorrect settings. Any of these scenarios may lead to crop damage. Situations where the tractor is actively steered away from the intended inter-row space or track (either by a Global Navigation Satellite System (GNSS) or by an operator) are not considered here as the wheels would then damage the crop.

To actively steer the implement and prevent crop damage, manufacturers have developed three main solutions:

1. Steerable axles/wheels on trailed/semi-mounted implements;
2. Installation of side-shift frames between tractor and implement; and
3. Side-shiftable lower links of a tractor.

Each of these is considered in turn. First, steerable axles on implements deliver an acceptable result in row crop systems such as potato planting. The system consists of a hydraulically-activated steering system, a camera that detects the rows and/or a GNSS receiver when using a Real Time Kinematic (RTK) or another GNSS system for machine guidance and accuracy. Due to the incompatibilities of various designs and the GNSS/camera components with the need of an acceptable user interface in the tractor, the adoption of such systems is low.

Secondly, side-shift frames are used commonly because no customized design of the implement is needed. A GNSS receiver or a camera to detect crop rows is still needed to maintain high accuracy, but, if this is not necessary, the driver can activate the hydraulically operated side-shift frame manually from the cab.

The third solution is very new and not yet commercially available. Side-shiftable lower links on the tractor eliminate the weight of the side-shift frame (ca. 0.7-1.2 t) and reduce the distance between the tractor and the implement by the length of the side-shift frame (0.5 m). Another benefit is the more rapid and direct reaction because of the reduction of the degrees of freedom (there is only one degree of freedom on the coupling point compared to at least two on side-shift frames). A GNSS receiver or row-detecting machine vision system is still needed to maintain high accuracy, but, if this is not necessary, the driver can activate the hydraulically operated side-shiftable lower links manually from the cab. A minor challenge for successful weeding is keeping machines on track is the rotational movement of the implement around a horizontal axis in the center of the tractor.

The importance of hoeing close to the crop row and the use of different intra-row hoeing tools demands very accurate steering in order to avoid damage to the crop (Van der Weide et al., 2008). High-speed weed management solutions demands a very fast response-time for all components, including steering, hydraulically-activated implements or tools, and automatically controlled sections of an implement. Therefore, tractors for professional growers are either sold with a GNSS guidance system achieving Differential (DGPS) or RTK accuracy, or these can be retrofitted after purchase. This should be considered as the basic requirements to perform mechanical weed management economically. Furthermore, very precise hydraulic flotation through electrical selective control valves (SCV's) allows precise steering of the implements to an accuracy of 10 millimeters or better.

In addition to these basic requirements, multiple GNSS-signals or camera-based, row detection information must be computed by the tractor's own computer system and the separate components and systems must be compatible (e.g. using ISOBUS). The additional information from an implement-mounted GNSS receiver or cameras corrects for changing offsets along the row and thereby leads to high level accuracy.

A special use case is the mechanical weeding in the row, which demands the highest level of accuracy on mounting, detection of crop and actuators to move tools in between the single plants (Moeller, 2010). First solutions are shown but are not ready for commercial farm usage due to high investment costs and possible lower speed. Here, an overlap is evident with autonomous, robotic weeders.

High definition weed mapping and site specific weeding

This paper has so far primarily focused on weeding the whole field. But, this section reviews and evaluates attempts and opportunities to apply precision agriculture methods (PA) to non-chemical weed control (NCWC) and the general prerequisite of knowing where the weeds are located in order to implement PA. In fact, since the beginning of agriculture, farmers have frequently utilized non-chemical PA approaches. More modern and developed farming techniques, whether non-chemical or conventional is often untargeted and imprecise: weeds are more easily controlled by treating whole fields. Site-specific weed management (SSWM), however, aims to manage the within-field variability in weed problems by applying the right treatment in the right place at the right time in order to optimize benefits.

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Weed mapping

But where is the "right place"? Accurate weed sensing and targeting are essential pre-requisites for many SSWM methods. Weed patches need to be mapped and geo-referenced. Lutman & Miller (2007) therefore stated that "few farmers have adopted site-specific weed management" because of "a great reluctance … to spend time creating maps. They would much prefer automated detection systems". Similarly, Gerhards & Christensen (2003) concluded that "weed monitoring systems are a critical component in the utilization of the ideas and knowledge developed in research projects on site-specific weed control". The lack of automated weed mapping is, therefore, a clear obstacle (Miller & Lutman, 2008)

Image capture and analysis are frequently used for weed sensing and mapping. Light intensity at the time of image capture can, however, affect performance and the ability to discriminate weed and crop plants due to changes in the red, green and blue components of the light. For example, Nieuwenhuizen et al.'s (2007) system correctly identified about 97% of volunteer potato plants in a sugar beet field under cloudy conditions, but this reduced to 49% under sunny conditions. Machine vision is particularly challenging as the canopy closes (Jafari et al., 2006) although this technical issue can be overcome using high resolution proximal sensing and appropriate software (Murdoch et al., 2014). However, using low resolution image capture, Rasmussen et al. (2013) detected weed patches from heights of more than 50 m using a remotely-piloted aircraft system (UAV). At this height, each image captured 0.3 ha with resolution of 17 m per pixel. This resolution is, however, insufficient to detect weeds at densities important to the farmer and ground-truthing is essential for weed species identification (Murdoch et al., 2014).

The need for the farmer to purchase such technology can be over-stated! Patches can be geo-located manually with a hand-held GPS receiver. Technology start-ups and companies increasingly offer cloud-based mapping services using images captured via satellites and such images are now free via the EU Sentinel satellite services. Others use manned aircraft, unmanned aerial vehicles (UAVs) or ground vehicles. Each approach has advantages and disadvantages but the challenging task of automated identification and geo-location of individual weed species without needing supplementary ground truthing demands a pixel resolution in RGB images of 0.3 to 1.25 mm (Murdoch et al. 2010), which is only achievable with a ground-based proximal sensing system. Systems achieving this spatial resolution across large fields have been developed but are not commercialised. The practical solution is to follow the general principle of automation: it is easy to automate 80% of a process but even though the last 20% may be technically feasible, it may not be an economic proposition. So some ground truthing is essential and it must be acknowledged that low densities may go undetected.

Technology required for SSWM using weed maps

The technology needed for weed mapping and SSWM includes an in-cab computer and software, a geo-referenced weed map interpreted into a treatment map, equipment capable of varying the SSWM method across the field in real time and a global navigation satellite systems (GNSS). The GNSS is freely available through satellite constellations such as the US-funded GPS, EGNOS (European Geostationary Navigation Overlay Service for GPS), the Russian-funded GLONASS and the European Galileo system. More precise geo-referencing is achievable using localization of signals for example to a base station.

Farm machinery must be loaded with the prescription maps which determine exactly where in the field to apply NCWM.

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Some NCWC options for SSWM using weed maps

In developed countries and in the EU in particular, treatment of weed patches via SSWM rather than whole fields could have great environmental and economic benefits especially for NCWM. These benefits accrue because the uniform use of NCWM across whole fields by physical methods such as inter-row tillage, use of tines or harrows or ploughing, is increasingly seen as detrimental. First, these methods incur significant energy use both in moving large amounts of soil and also in replacing worn machinery. Moreover, cultivation may also increase greenhouse gas emissions by stimulating oxidation of soil organic matter and mineralisation of organic nitrogen. Furthermore, soil disturbance damages soil structure and increases the likelihood of wind and water erosion as well as adversely affecting the soil macro- and meso-fauna. Ironically, controlling weeds by cultivation has the undesirable though inevitable consequence of stimulating weed seed germination from the soil seed bank, so creating a vicious circle. With its all too frequent dependence on intensive tillage, NCWC can, therefore, have significant adverse environmental impacts. Applying SSWM to NCWC is, therefore, important to harness the benefits of NCWC in reducing herbicide inputs and also to reduce its negative impacts, thereby enhancing resource use efficiency and increasing the sustainability of food production.

Not all site-specific non-chemical methods have negative side effects. For example, variable rate seeding allows farmers to increase the seed sowing rate in zones known to have had serious weed infestations in the previous crop – although clearly, a weed map is essential. For example, Mahmood and Murdoch (2017) found that the patches of higher weed densities in sugar beet tended to occur in the areas of low crop plant population density. Increasing seed rate in areas of fields where high weed densities were detected in the previous crop or where soil conditions are less favourable to crop establishment could help to mitigate the effect of weeds.

Non chemical weed control (NCWC) and site specific weed management (SSWM) and precision agriculture without weed maps

Looking ahead, row crops are particularly well-suited to robotic plant-specific weed control, and while the efficiency of these systems could be enhanced with weed maps, the operating principle is that of real time weed sensing and treatment. So a weed map is not a prerequisite. Such crops are often relatively high value and they may be precision planted or transplanted and have wide row spacing. So weed sensing and 'mapping' can be reduced to the statement: "if the plant detected is not in the crop row or at the correct location in the crop row, it should be eliminate". The robotic weeders working in transplanted crops mentioned earlier in this paper is an example of these systems.

Overcoming barriers to adoption of NCWM and SSWM

Why do most farmers apply treatments across whole fields? Clearly some do not have the right machinery and the economic benefits need to be demonstrated. There is also a risk aversion associated with the real possibility that a bird or a deer or a piece of farm machinery or a dog walker or even an agronomist might have moved a single viable seed from a dense patch to a 'clean' part of the field. Uncertainty about the stability of weed patches may also be a factor if the weed maps are based on weeds detected in a previous crop. Near real-time sensing at early crop growth stages using UAVs may alleviate many concerns, but the inability to detect individual weed plants may still make farmers unwilling to invest or take the risk.

So how should these barriers to adoption be overcome? The critique in the EIP-AGRI Precision Farming report gave a simple message:

> *"Most research in Precision Farming still concentrates on developing and testing sensor and sensing technology. Specifically in Precision Arable Farming key applications have*

> *focused on the use of sensor technology … so that … data-gathering methods … using innovative sensors have made tremendous progress, but decision-making that is based on collected data needs further research."*

So how can a farmer's failure to decide to adopt precision weed management be overcome? It is suggested that economic analyses should not only predict the expected costs and benefits, but they should evaluate the probability of making ***more*** profit. Decision-making will never be completely reliable, but rather than presenting the manager with a single threshold value of acknowledged unreliability, such an approach would give the manager an estimate of ***the probability*** that controlling an actual infestation by SSWM will be profitable.

Single plant detection and non-chemical weed control

Within North-West Europe the main arable crops are sugar beet, onions, carrot and potatoes. Major weeds are volunteer potatoes and carrot weeds. Though, all other weeds are an important limiting factor in arable crop production as well. For the purpose of single plant detection and non-chemical weed control several aspects need to be distinguished. First part is the detection, second part is the control of the weed. When it concerns the detection part, two methods exist for detection of areas that need to be controlled, or areas in which weeds need to be removed. One method is detection of the crop plants, and all other areas need control, regardless of the presence of weeds. The other method is detection of weed plants, and only apply control on the location of the weed plants. When control of weeds is required with minimal inputs of energy, and in a sustainable way not disturbing more soil than necessary, only individual weed plant recognition is a good solution. Detection of crop plants is not enough for effective and efficient weed control with minimal inputs of energy, as large bare soil areas will be treated or disturbed, having negative impacts on the growth conditions of the crop. One can think of excessive evaporation, loss of water or germination of new weed seeds due to soil disturbance effects.

For the purpose of single weed plant identification and localisation several techniques are available. As of 2019 large databases are available containing images of weed species in several growth stages. These databases can be used to train realtime deep learning neural networks. For training deep learning classification networks, large numbers of weed examples images are necessary, and adaptation of training data is necessary to handle new crop and weed types during the season and between seasons. For single plant detection, drone and satellite imaging are not yet accurate enough. This is due to error build up in positioning and image rectification (Bah et al. 2018), this error build up is too much to accurately control the weeds in a second stage. For single plant weed control, detection and control must be performed in a one stage setup. Using these machine vision and camera techniques, single weed plants can be identified. Of course depending on the growth stage, detection results are changing and improving for larger growth stages of weeds. To effectively control the weeds, not only the weed location and weed species is required, also weed growth stage and leaf biomass would be needed. One can imagine that a small weed requires less energy or mechanical damage to be controlled compared to a larger weed. A detection system would ideally also estimate the crop growth stage as well, to properly set thresholds on allowed crop damage, and to estimate and adjust the weed control method to stay within acceptable limits. With current 2019 camera technologies weed plants can be detected up to the square mm precision. This means that contours of leaves can be identified, as well as centers of plants and total leaf area of weeds. It is however still challenging to find positions where the weed is actually going into the soil. So the root positions are mostly unknown from camera detection results. Some of the control methods would preferably have this root position information as well to better target the control method. Current camera based detection system, either regular colour RGB cameras or including hyperspectral cameras, have a resolution of approximately 1 square millimeter to assess the weed species and the weed location. Most camera systems on the market for weed detection do not have an actuator directly in the field of view of the camera, and therefore the actual accuracy is influenced by the movement of the machine between detection and control as well. As soon as the single plant position and weed plant parameters have been identified, several options are available to control the weeds (Tu et al. 2001). Some of the available methods are: electrocution, laser cutting or damaging, precision flaming, defoliation by cutting, mechanical damaging, push into the ground or punch, pull the weed. Some of these methods seem impractical, though are being used in research for quite a while with increasing success rates. The technologies for micro mechanical adjustment of laser optics have increased a lot since the 2010's, with increased availability of components suitable for laser cutting and damaging. Electrocution devices have been changed and improved to work on larger scale as well, they need to be adapted for single plant use, and need special attention not to kill or damage the crop in the 2 close to crop region. Simply removing the above ground biomass might already kill some of the weeds, or exhaust weeds with large energy reserves in the roots. Overview of techniques mentioned with remarks: Detection: - Machine vision camera's with deep learning classification. Large amount of training data is required. Smart learning algorithms are in development to automate training. Root location is still unknown. Plant detection accuracy is high. - Hyperspectral camera's and classification. Expensive camera technology. Most of the information for weed detection is available in RGB camera images as well. - Fluorescence camera's and classification. Fluorescence is strongest for chlorophyll content in plant parts. Other fluorescence effects are only marginal, therefore distinguishing different plants or crops and weeds from fluorescence only is difficult. Actuation: - Electrocution is a very effective method to control both above ground and below ground root parts of weeds. Methods to properly control smaller weeds and root weeds within crops are under active development in research. Especially the distance to the crop plant and the moisture content of the soil are important parameters to adjust. - Laser light is an effective method to concentrate energy in a small point. Laser light can be easily targeted with micro mechanical instruments towards the growth point of a weed plant. Energy consumption and accuracy can be a challenge. - Cutting with a rotating blade or knife is the mechanical counterpart of laser weeding. Limiting factor is that to cut the weed in the right place, very accurate information on the weed plant location is required, as well as to the root position where the plant is entering the soil. - Damaging is the easiest part. It is basically cutting in a more coarse way. The challenge is not to disturb the soil too much and still uproot the weeds. - Push or punch is a more effective way of damaging. It is setting back the weed in an effective way, minimizing soil disturbance. It has been tested in practical proof of concept machines. - Pull a weed is the most advanced way. It requires efficient gripper technology to clamp on the weed. Then appropriate force needs to be applied to pull and also uproot the weed. It is an effective way of weeding, though the biggest challenge is to mimic the human behavior and sensing required for this.

Conclusions

Today, mechanical weeding is increasing in popularity as options for use of herbicides decrease in conventional farms. Problematic weed management (due to herbicide resistance, lower efficacy of chemicals due to timing of application, weather-indicated lower efficacy) is also acting as a driver for adoption of mechanical solutions. But apart from in organic farming systems, mechanical options must compete with established herbicidal solution, by becoming faster, more effective and less expensive especially in small grains. Political and socio-environmental push and Ag-market pull are also evident drivers and will help to open the market for such solutions.

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