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CURRENT ACHIEVEMENTS AND FUTURE DIRECTIONS OF PHYSICAL WEED CONTROL IN EUROPE

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RESUMÉ

LUTTE PHYSIQUE CONTRE LES ADVENTICES : ÉTAT ACTUEL ET PERSPECTIVES EN EUROPE

Cette publication rapporte les principaux résultats obtenus avec les stratégies et les méthodes physiques de contrôle des mauvaises herbes, spécialement conçues pour les cultures horticoles et les grandes cultures. Les méthodes mécaniques, comme le hersage et le binage de l'inter-rang ont donné des résultats prometteurs en céréales, légumineuses à grains et colza, en particulier quand elles s'intègrent dans des stratégies qui impliquent des méthodes culturales telles que le positionnement des engrais ou l'utilisation de semences à forte vigueur. Dans les cultures en ligne, le désherbage du rang constitue un défi majeur et la recherche s'est surtout dirigée vers le remplacement du désherbage manuel par une mécanisation. De nombreux essais ont visé à améliorer l'utilisation des méthodes thermiques et mécaniques pour détruire les mauvaises herbes sur le rang.
De nouvelles méthodes sont actuellement testées, comme le désherbage à l'aide de robots pour les cultures en ligne présentant un espace important entre les pieds et le désherbage à la vapeur, localisé, pour celles à forte densité sur la ligne.

Mots-clés : désherbage mécanique, désherbage thermique, désherbage intelligent, stratégies, non chimique

SUMMARY

This paper reviews major results achieved with physical weed control methods and strategies especially adapted for horticultural and agricultural crops. Mechanical methods, such as weed harrowing and inter-row hoeing, have provided promising results in cereals, pulse and oil seed rape, particularly when they are part of a strategy that also involves cultural methods such as fertiliser placement or crop seed vigour. In row crops, intra-row weeds constitute a major challenge, and research has mainly aimed at replacing laborious hand weeding with mechanization. A number of investigations have focussed on optimising the use of thermal and mechanical methods against intra-row weeds. And new methods are now under investigation such as robotic weeding for row crops with abundant spacing between individual plants and band-steaming for row crops developing dense crop stands.

Key-words: Mechanical control, thermal control, intelligent weeding, strategies, non-chemical

INTRODUCTION

Non-chemical means, such as conscious choice of crop sequence, tillage tactics, direct mechanical methods and hand weeding, were common tools to manage weeds prior to the introduction of selective herbicides in the late 1940s. Then a strong reliance on herbicides for weed control followed in the succeeding decades and very little attention was given to non-chemical methods. However, physical and cultural weed control methods has acquired renewed interest since the mid-1980s and has steadily increased up through the 1990s in many European countries, notably Sweden, the Netherlands, Germany, Italy, UK, Switzerland, and Denmark. This development has largely been driven by an increasing concern about pesticide usage. Governmental actions have now been taken in the Nordic countries and the Netherlands to introduce action plans to cut pesticide usage significantly. An increasing conversion to organic farming, favourably subsidised by some European governments, has followed this pesticide policy and further increased the need for knowledge on non-chemical weed control.

Consequently, considerable public research funding has been granted to develop physical and cultural weed control methods, which has resulted in more knowledge and information on non-chemical methods for horticultural and agricultural crops than previously known in Europe. Apart from scientific publishing, most of the European work is discussed and disseminated through the working group on Physical and Cultural Weed Control (www.ewrs.org/pwc) organised under the European Weed Research Society. The group's main activity is its workshops held at 2-3-years interval (proceedings from the meetings in 2000, 2002 and 2004 are available at http://www.ewrs.org/pwc/archive.htm). A wide range of direct physical methods (*i.e.* those used directly in the crop after the crop is either transplanted or sown) have been introduced and studied, some of which are new principles, while others are old principles that have been subjected to new research. Also preventive and cultural methods have been an important part of the term 'non-chemical weed control' and especially their interactions with direct methods have had substantial interest in recent research.

This paper reviews major results achieved with physical methods and strategies especially adapted for the control of annual weeds in row crops (*e.g.* maize, sugar beet, onion, leek, cabbages and carrot) and crops with narrow row spacing (*e.g.* barley, wheat, peas, oil seed rape and lupin). It also highlights some of the future directions. For those interested, the reviews by MELANDER *et al.* (2005) and BOND & GRUNDY (2001) give more comprehensive expositions of the subjects presented here. Illustrations of the majority of the many implements and weeding devises mentioned in the text can be seen in BOWMAN (1997).

MECHANICAL METHODS

Mechanical weed control methods are the most common physical methods used in practise and a wide range of implements is available for agricultural and horticultural crops. They are considered low-tech solutions with relatively low purchase and operation costs. The weeding mechanism of mechanical tools is mainly by uprooting and/or burying the weeds (*e.g.* KURSTJENS & KROPFF, (2001)).

Whole crop treatment

Among crops having narrow row spacing (typically 10-15 cm), weed harrowing has mostly been studied for its use against annual weeds in small grain cereals (*e.g.* RASMUSSEN, 1991), although its potential for weed control in pulses is also evident (*e.g.* JENSEN *et al.* 2004). Weed harrowing treats the whole crop and is usually conducted with a spring-tine harrow but other manufactures can be used as well. In the beginning of the 90s, the principles of pre-emergence, post-emergence and selective weed harrowing (Figure 1) were introduced (RASMUSSEN & SVENNINGSEN, 1995). It was found that pre- and post-emergence harrowing most effectively controlled problematic weed species with an erect and fast growth habit, such as *Tripleurospermum inodorum* and *Papaver rhoeas*, and particularly when the two principles were combined. However, early post-emergence harrowing in the early growth stages of the crop may be accompanied by serious crop injuries, which can cause yield loss. It is important to match the intensity of weed control to the need, since at a certain point of intensity, crop injury will over-shadow the effect of weed control as the intensity of soil cultivation is further increased. Selective harrowing is used at later crop growth stages than the other two principles, typically from the end of tillering to early stem elongation. The crop is more tolerant to harrowing at these stages, and the treatment can be done at high driving speed. Selective harrowing only controls weed species that are weakly rooted with prostrate growth habits (e.g. *Stellaria media* and *Veronica persica*). A strategy consisting of pre-emergence harrowing followed by post-emergence harrowing and sometimes even selective harrowing may result in weed control levels similar to those common for herbicide treatments.

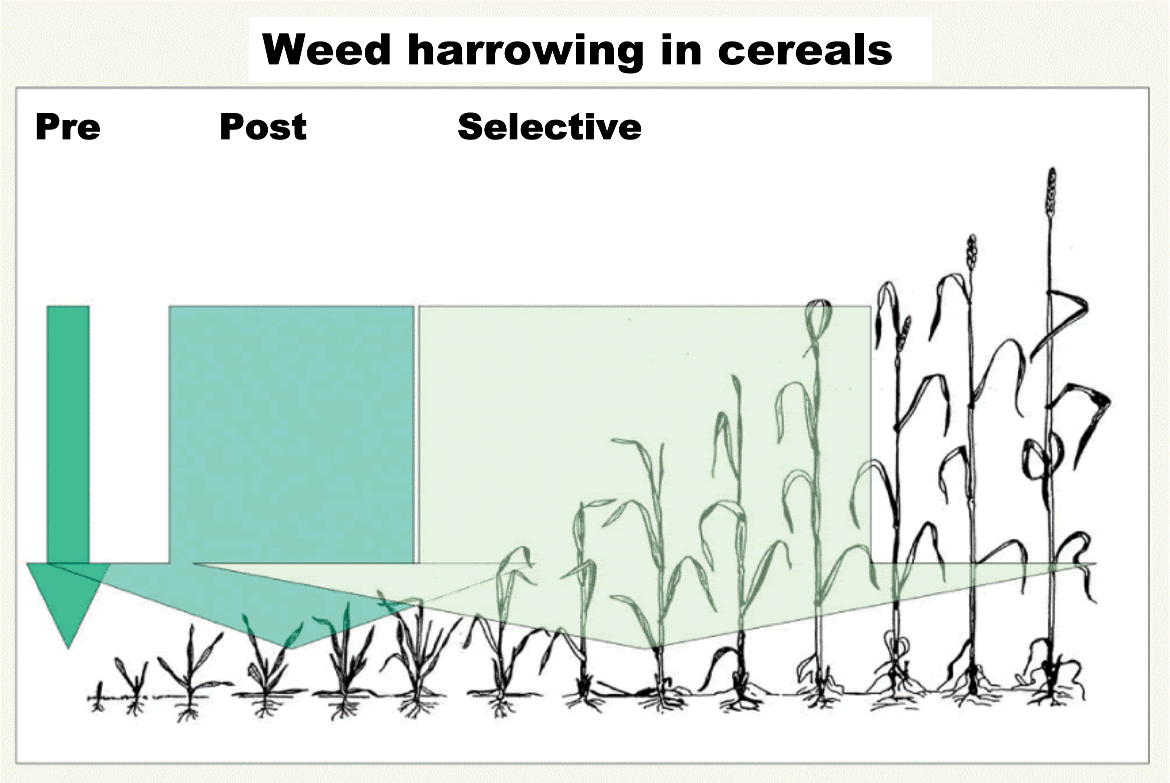

Figure 1. Illustration to show the timing of pre-, post-emergence and selective weed harrowing in cereals according to the growth stage of the crop.
(Epoques possibles de passage de herse pour désherber des céréales en pré ou post-levée ou en végétation).

Inter-row control

Widening the inter-row spacing to more than 20 cm in cereals allows inter-row cultivation to take place in the inter-row area. Inter-row hoeing with hoe blades configured either as a ‘ducks-foot’ or ‘A-width’ shape has been found to control tap-rooted and erect weed species growing in the inter-row space more effectively than harrowing (*e.g.* MELANDER *et al.*, 2003). Inter-row hoeing is also less sensitive to treatment timing because even well anchored weeds can be uprooted. Hoeing is a highly selective control method and results are not greatly affected by soil moisture and soil type. Thus, inter-row hoeing can be postponed to the spring in winter cereals, where the crop is less vulnerable, without lowering the effectiveness against the weeds. However, accurate steering is essential to avoid severe crop damage, and the steering task is a significant constrain to a wider application of inter-row hoeing in cereals.

Inter-row cultivation in typical row crops, where inter-row spacing is even larger (50-70 cm), usually works successfully in most situations, because the crop plants are not directly affected by the weeding tools and moreover can be shielded in different ways. Inter-row cultivation is regularly used both in conventional and organic row crops and has in many cases replaced chemical weed control in conventional winter oil seed rape grown at 50 cm row spacing in Denmark. Ordinary steerage hoes with blades mounted on either S-tines or shanks are normally used for inter-row cultivation, but other cultivators such as rotary hoes, rolling cultivators and power take-off (PTO)-driven cultivators are also used. Several new implements have been introduced recently where multiple mechanical tactics have been included to improve effectiveness.

Manual steering has been the common way for decades to keep the inter-row cultivators in the right position to avoid crop damage. However, new electronic guidance systems have been introduced recently to ease the steering task. They are based on computer vision technology for the detection of crop rows (TILLETT *et al.*, 2002) and are capable of steering hoes and other implements automatically along a crop row (WILTSHIRE *et al.*, 2003). Automatic steering seems to have potential even for row hoeing in cereals (Figure 2). The new systems are believed to improve the working situation for drivers (less concentration needed); the working capacity by increasing driving speed and width of the implements; and the closeness to the crop plants at which the hoe blade can work. For some of the systems, it is claimed that the precision can be lowered to ± 15 mm deviation from a centre line at a driving speed of up to 10 km h^{-1}. However, an experimental verification of those claims still remains to be seen for a number of crops and field situations, such as sloping fields, different crop leaf architectures and growth habits, and poor crop stands blurring the row structure.

Figure 2. Inter-row hoeing in organic cereals (50 cm row spacing) with an automatic steering system. The yellow box on the hoe frame contains two cameras for row detection. (Binage inter-rang à guidage automatique en céréales organiques. La boîte jaune contient 2 caméras permettant la détection des rangs).

Intra-row control

While inter-row weeds can be removed by ordinary inter-row cultivation relatively easily, intra-row weeds, *i.e.* those growing between the crop plants in the rows, constitute a major challenge. For inter-row hoeing in cereals and oil seed rape grown at increased row spacing, the only effect on intra-row weeds achievable are the amount of soil coverage caused by hoe blades throwing soil into the row and the suppressive ability of the crop.

However, typical row crops offer better opportunities for more specific intra-row weed control. In sugar and fodder beets and most vegetables, research has mainly aimed at replacing laborious hand weeding with mechanization. Several mechanical methods have application for intra-row weed control in these crops but as with most other mechanical weeding implements, operator skill, experience, and knowledge are critical to success. Drawbacks to mechanical intra-row methods include poor seedbed preparation resulting in soils difficult to till, low work rates, delays due to wet conditions, and the subsequent risk of weed control failure as weeds become larger. Weed harrowing with spring-tine, chain or drag harrows may be used, but the spring-tine harrow with flexible tines is probably the most preferred one with the widest range of applications (*e.g.* BÀRBERI *et al.*, 2000). Similar to cereals, it can either be used prior to crop emergence or post emergence, and it involves weeding the whole crop. Torsion weeders, with pairs of tines set on either side of the crop row and lowered 2-3 cm into the soil offer more precise intra-row control but steering becomes crucial, normally including a second operator to specifically steer the implement. Finger-weeders, with flexible rubber tines on ground-driven cone-wheels, were also developed specifically for intra-row weed control. Vertical brush weeding, with brushes rotating around vertical axes and placed in pairs to cultivate either side of the crop row, is a relatively new method that emerged in the early 90s (MELANDER, 1997). The torsion weeder, finger weeder, and brush weeder are all mainly developed for post-emergence use in high value vegetable crops because of their low working capacity.

Results with mechanical weed control have been particularly good in transplanted row crops such as cabbage, celery, leek, onion, and sugar beet (ASCARD & FOGELBERG, Swedish University of Agricultural Sciences, Alnarp, Sweden, personal communication; MELANDER, 2000), where transplanting itself creates very favourable conditions for mechanical weeding, because large crop plants are established in a newly cultivated soil. Provided that the crop plants are well anchored, they can withstand mechanical impact even a few days after transplanting where the first flushes of weed seedlings normally are emerging and need to be controlled. Transplanted crops also gain a competitive advantage over the weeds as compared to sowing the crop, which gives a better suppression of weeds that may have escaped control. However, current techniques for transplanting are only profitable in some highly valuable vegetable crops and need to be further developed to become cost effective in other row crops.

The use of a rolling cultivator with spider gangs or a combination of weed harrowing and disk hilling is another example where effective inter-row and intra-row weed control can be successfully implemented with no need for supplementary control measures (RASMUSSEN, 2002a).

THERMAL METHODS

Flaming prior to crop emergence has been the predominant thermal weed control method in slow germinating row crops such as onion, leek, carrot and maize. Pre-emergence flaming is only of limited value in fast emerging crops, such as kale, because the crop may easily emerge before most weeds, making flaming useless. There are two fundamental types of thermal weeders on the market: the covered flamer, flaming to 1900 ^{o}C, or the infra-red weeder, with essentially no visible flame and heating to 900 ^{o}C. Both use liquefied petroleum gas or propane/butane mixtures as fuel. The advantages of flame weeding are that it leaves no chemical residue in the soil and water and does not disturb soil, but it has disadvantages in its high consumption of costly fossil fuels. Flaming kills weeds that have emerged prior to the crop, mainly by rupturing the cell membranes and the indirect effect of subsequent desiccation. The effect of flame weeding varies with plant size; plants at 4–12 leaves required 2–4 fold higher energy rates for control than those at the 0–4 leaf stage (*e.g.* ASCARD, 1994, 1995).

Mobile soil steaming prior to crop establishment has acquired additional attention recently owing to its potentially very high effectiveness leading to almost complete weed control over long periods. Addition of compounds such as CaO or KOH can further increase weed control by boosting soil heating through exothermic reaction with the steam, reaching peak temperatures >80°C at 15 cm depth. Experiments carried out in Italy showed that addition of KOH at 4000 kg ha^{-1} reduced the total weed seedbank by 76% compared to steaming alone and that the rate of seedling emergence decline for any 100 kg increase in KOH rate was 58 seedlings m^{-2} (MOONEN *et al.*, 2002). However, an extremely high consumption of fossil energy and low work rates are major disadvantages of current soil steaming technology.

Steaming can also be used post-emergence against aboveground weed vegetation. The same applies for microwaves, hot water, freezing using liquid nitrogen or carbon dioxide snow, ultraviolet light, CO_2 laser cutting, hot foam and dry heat. However, most of these methods have generally very little practical use and some of them are still in their infancy from a scientific point of view. Major disadvantages with most thermal weed control methods for post-emergence usage are the energy consumption, low work rates and sometimes unpractical application techniques.

SELECTIVITY

Mechanical intra-row methods generally operate with low selectivity, especially in drilled row crops having slow emergence and low initial growth rates, such as drilled onion and leek, and under cool North European weather conditions sugar beets and silage maize as well. Low selectivity means that a high weed control level might be associated with severe crop injuries, particularly if large weeds are to be controlled satisfactorily. It is essential that the crop has a size advantage over the weeds when implement settings cause the weeding tools to impact the crop plants directly, which may be necessary to achieve sufficient control. For example, sugar beets need to have developed 4-6 true leaves and drilled onions a height of more than 10 cm before they can tolerate direct contact with mechanical weeders. Cereals are generally more tolerant but early post-emergence harrowing in the early growth stages of the crop may be accompanied by serious covering of the crop with soil, which can cause yield loss (RASMUSSEN, 1991).

Thermal methods applied post-emergence are even less selective than mechanical methods. Drilled onions are able to regrow after flaming at the flag-leaf stage but yield decreases may occur. Maize and set-onions can tolerate flaming, provided that the flames only hit the base of the plants and other plant parts are shielded from the heat. Shielded post-emergence flaming is only effective against small sized weeds and obviously the crop needs to be considerably larger than the weeds to make this method operational.

Combinations

Mechanical post emergence methods have to be combined with methods applied pre-emergence to overcome or lower the problems with poor selectivity. Strategic approaches in which two or more methods are combined into a specific control strategy adapted to the actual weed problem have provided some promising results. Pre-emergence methods control the first flushes of weed seedlings that emerge before the crop, and thus delay further weed emergence and growth relative to the crop, allowing the crop to gain a size advantage over the weeds. For example, pre-emergence flaming followed by post-emergence vertical brush weeding gave 90% intra-row weed control over two years of experiments in drilled leek (MELANDER & RASMUSSEN, 2001). The combined effects of these treatments were not a result of synergistic interactions, but rather that each treatment controlled certain cohorts independently of the preceding treatment. As mentioned earlier, combining pre- and post-mergence weed harrowing and finally selective weed harrowing may provide very good results in spring-sown cereals. And combining inter-row hoeing with weed harrowing is usually better than applying the same number of passes with one of the methods only.

Preventive and cultural methods

Preventive and cultural methods are regarded as measures that may improve the outcome of physical intra-row weeding by contributing to the reduction of weed numbers and by improving growth, competitiveness, and robustness of the crop plants, more than that of the weeds. For cereals with a strong competitive ability, combinations with cultural methods such as fertiliser placement, variety choice, crop seed vigour and crop seed rate may improve the outcome, especially by improving crop competitiveness against weeds escaping control. For example, giving crops better access to nutrients than weeds augments crop competitiveness (Figure 3) (RASMUSSEN, 2002b). Most annual weeds germinate from the top few mm of the soil, nutrients broadcast on the top of the soil, or worked into the top 5 cm, will give the weeds equal opportunity to utilize these nutrients together with the crop. Placement of nitrogen, *e.g.* 1-5 cm from the row and 5 cm deep in the soil, may improve early nitrogen uptake and crop growth, thus the crop gains an initial competitive advantage over weeds, and may result in up to 50% reduction in weed biomass.

However, whether these methods really add such positive effects to physical weed control strategies in row crops also has not been unambiguously proven in the relatively few studies made on this subject.

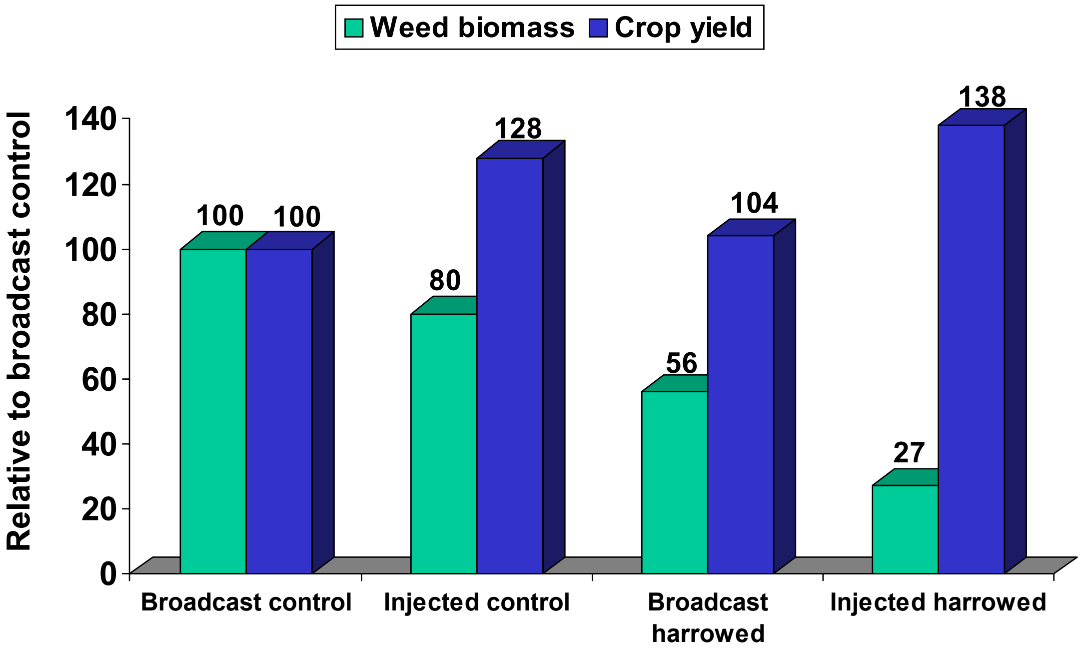

Figure 3. Effects on barley grain yield and weed biomass of broadcasting and injecting slurry. Slurry was injected between the rows of cereals and down to 5-8 cm soil depth (adapted from RASMUSSEN (2002)).
(Effets de l'apport en plein ou localisé de boues sur le rendement en grain de l'orge et sur la biomasse des adventices. Les boues sont injectées dans l'inter-rang des céréales à 5-8 cm de profondeur).

FUTURE DIRECTIONS

A major problem with current physical methods is that they do not distinguish between weed and crop plants. There are no indications currently that new technologies could substantially change the situation in cereals, pulse and oil seed rape grown at narrow row spacing. There is no possibility of operating a weeding devise in the inter-row space that selectively could remove intra-row weeds. Also the fact that crop plants are established in dense stands in the rows with very little spacing between individual crop plants is another strong limitation for selective physical intra-row weeding. Widening the inter-row spacing would not improve the possibilities since crop stands in the row are still dense. So for the time being, research should aim at optimizing weeding strategies that combine mechanical methods with cultural and preventive measures to improve overall weed control.

However, row crops having more space between individual plants, both inter-row and intra-row, open up new perspectives for selective intra-row weed control. So far, no commercial automated physical methods have been developed for weeding the intra-row or close-to-crop area, which currently requires substantial input of hand weeding in most herbicide-free row crops. The inclusion of advanced technology for intra-row weeding might become a breakthrough in physical weed control in row crops leading to significant reductions, or even elimination, of the need for hand weeding. The major obstacle for the development of selective and accurate intra-row weed control is the lack of automated detection and classification of crop and weeds. Requirements for an automated intra-row weeder to operate with high accuracy become particularly crucial when operating close to individual crop plants. HEISEL *et al.* (2002) showed that the closer weed plants were growing to sugar beet plants, the more they lowered beet yield resulting from severe competition. Also the time of weed cutting in sugar beets, using just one cut, was studied and indicated that cutting should take place rather late in the season as compared to common weeding time in sugar beets. Earlier cutting would allow for weeds to regrow and later cutting would result in too much weed competition. Some researchers are looking at systems for active shape modeling of weed seedlings to distinguish them electronically from crop plants (SØGAARD, 2005). Others have looked on vision based perception systems to discriminate between crop and weed plants using images from real situations in the field (ÅSTRAND, 2005). Attempts are made to use electronic crop seed mapping to assist subsequent computer vision for identification of crop and weed seedlings. Crop seed positioning at sowing uses the technology of Real Time Kinematics DGPS to create an electronic field map with geo-referenced seed positions for each individual crop seed. The seed map data can then be used for guiding a vision camera to the approximate positions of the crop seedlings. From these position estimates, a very accurate map of crop seedlings can be produced and thereby form the basis for precise weeding in the close-to-crop area (GRIEPENTROG *et al.* (2005)). Yet, none of the technologies mentioned, including other approaches, have developed into operational weeding systems. The research is, nevertheless, an important path to follow as advanced technologies are evolving so rapidly in these years and may change the prospects radically in a few years time.

Intelligent intra-row weeding systems appear mainly to become operational in row crops with abundant spacing between individual plants, whereas another technology based on soil steaming prior to crop establishment seems more promising for row crops developing dense crop stands in the row. With band-steaming, only a limited soil volume is steamed, just enough to control weed seeds that would otherwise germinate and emerge in the rows (MELANDER *et al.*, 2004; MELANDER & JØRGENSEN, (2005)). This technology already has lead to operational machinery for band-steaming in the field.

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