Mechanical, thermal and robotic weeding for minimising laborious hand-weeding in row crops

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Abstract

Intra-row weeds constitute a major challenge in organic row crops 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 and this paper reviews the major results achieved for horticultural and agricultural row crops. Mechanical methods, such as weed harrowing, finger weeding and torsion weeding, have provided promising results in transplants. In direct-sown row crops, however, successful weed control requires a strategy where mechanical methods applied post-emergence are preceded by pre-emergence flaming for the control of early and problematic weed cohorts. New methods, such as robotic weeding for row crops with abundant spacing between individual crop plants and band-steaming for row crops developing dense crop stands, have been introduced recently. They are seen as the future directions of new solutions for intra-row weed control in row crops.

Introduction

Time consumption for hand-weeding of intra-row weeds constitutes an appreciable financial burden in organic row crops in Europe and elsewhere. Intra-row weeds are those that grow within the line of crop plants of a row crop and they are usually not affected by inter-row cultivation. Manual intra-row weeding can be very laborious in vegetable crops, such as carrot and direct-sown onion and leek, which all have slow emergence and low initial growth rates. Time consumptions of 100 - 600 h ha^{-1} for hand weeding those crops have been reported for Denmark and Sweden. Transplants are far less demanding, requering only 24 - 45 h ha^{-1} for hand-weeding lettuces and cabbages (Melander *et al.* 2005; Van der Weide *et al.* 2008).

Due to the need for manual input in row crops, physical weed control methods has acquired great interest in many European countries. Considerable public research funding has been granted to develop new methods, which has resulted in more information on non-chemical methods for intra-row weed control in row crops. 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 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 studied, some of which are new principles, while others are old principles that have been subjected to new research.

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This paper reviews the major results achieved with physical control methods and strategies especially adapted for the control of annual intra-row weeds in row crops, such as maize, sugar beet, onion, leek, cabbages and carrot.

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. Most of them 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.

While inter-row weeds can be removed by ordinary inter-row cultivation relatively easily, mechanical intra-row weeding constitute a major challenge. Several mechanical methods have application for intra-row weed control in row crops but as with most other mechanical weeding implements, operator skill, experience, and knowledge are critical to success. Drawbacks 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 (Melander *et al.* 2005). 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. 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 (Melander *et al.* 2005; Van der Weide *et al.* 2008).

Results with mechanical weed control have been particularly good in transplanted row crops such as cabbage, celery, leek, onion, and sugar beet. 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.

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 partly 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 °C, or the infra-red weeder, with essentially no visible flame and heating to 900 °C. Both use liquefied petroleum gas or propane/butane mixtures as fuel. The advantages of flame weeding are that it leaves no chemical residues in the soil and water and does not disturb the 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 (Ascard *et al.* 2007). Band-steaming is a new concept that only heats a limited soil volume of the intra-row area, enough to control weed seedlings that would otherwise emerge in the rows (Melander & Jørgensen 2005). The energy consumption is approx. 600 l ha^{-1} of diesel fuel, which is far less than the 3,500-5,000 l ha^{-1} known for mobile soil steaming on raised beds. Band-steaming provides longer-lasting reduction of seedling emergence than e.g. flaming (Ascard *et al.* 2007). It is applied before crop sowing with no associated crop injuries, since the crop seeds are sown after the soil has cooled down. Inter-row weeds are controlled by cultivation. Band-steamers are now operating on a commercial basis in organic vegetable production in Scandinavia as a result of this work. On-farm studies in Sweden have shown that a nine-row band-steamer, treating 105 mm wide bands, 50 mm deep, consumed 8000 l ha^{-1} of water and 570 l ha^{-1} of diesel fuel to achieve 90% intra-row weed control (Ascard *et al.* 2007). Normally a maximum soil temperature of 80°C should ensure satisfactory weed control under moist soil conditions, especially if the soil is cultivated prior to steaming to reduce the size of soil aggregates (Melander & Kristensen 2011). The majority of weed species in Danish arable soils emerges predominantly from the upper 0-20 mm soil layer and is thus affected by band-steaming. However, species having large seeds with the ability to emerge from below 50 mm may escape control. With a treatment time of 8 h ha^{-1}, band-steaming becomes very costly but need to be compared to situations where 100-600 h ha^{-1} of hand-weeding is the only alternative in e.g. organic carrot, onion and leek (Melander *et al.* 2005).

Combinations

For direct-sown row crops, mechanical post-emergence methods usually have to be combined with methods applied pre-emergence to minimise problems with low selectivity. Low selectivity means that a high weed control level can be associated with severe crop injuries, because the weeding tools do not discriminate between crop and weed plants. 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.

Future directions

A major problem with many physical methods is that they do not distinguish between weed and crop plants and need to be steered accurately or used in particular robust crops to avoid severe crop injuries. New and advanced technologies for intra-row weeding are regarded as highly important for solving problems with poor selectivity. Advanced technologies with the ability to automatically detect and classify crop and weeds for guiding a weeding devise, operating in the intra-row area, would mean major step forward. Thereby problems with unwanted crop impact from weeding tools can be avoided, meaning that intra-row weed control can be conducted with high selectivity (Van der Weide *et al.* 2008). Most recently two new robotic weeders have been introduced, namely *Robocrop* from England (http://www.garford.com/inrow.html) and *Robovator* from Denmark (www.visionweeding.com). Both systems are vision-based where cameras mounted on the implement are capable of analysing images of the crop immediately in front of the weeder. Thereby the weeding tool can be guided to work a certain area around each crop plant without impacting the crop. Only few experiences have been achieved with the new robotic weeders until now but the technology looks promising when operating in transplants with abundant space between crop plants. Especially, more data on work rate and operational reliability when operating close to the crops plants are needed before making more solid evaluations of their potential for row crops. Band-steaming is still regarded as the most promising method for row crops having dense crop stands in the rows with little space between individual crop plants. Weeding robots are not likely to become operational in such situations unless new technologies turn up. However, any modifications of the band-steaming technology that could reduce the energy input, including changing the energy source from fossil energy to biofuels, should have high priority in future research. Although band-steaming is currently accepted in Danish organic farming, the technology is still controversial in view of potential climate change and the desirability of reducing greenhouse gas emissions.

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