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Symposium

Integrating physical and cultural methods of weed control—examples from European research

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Increasing concerns about pesticide use and a steadily increasing conversion to organic farming have been major factors driving research in physical and cultural weed control methods in Europe. This article reviews some of the major results achieved with nonchemical methods and strategies, especially adapted for row crops (e.g., corn, sugar beet, onion, leek, and carrot) and small-grain cereals (e.g., barley and wheat). In row crops, intrarow weeds constitute a major challenge, and research has mainly aimed at replacing laborious hand-weeding with mechanization. A number of investigations have focused on optimizing the use of thermal and mechanical weeding methods against intrarow weeds, such as flaming, harrowing, brush weeding, hoeing, torsion weeding, and finger weeding. 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. The strategic use of mechanical weed control methods in small-grain cereals has been another area of considerable interest. Weed harrowing and interrow hoeing provide promising results when they are part of a strategy that also involves cultural methods such as fertilizer placement, seed vigor, seed rate, and competitive varieties. Although research in preventive, cultural, and physical methods have improved weed control in row crops and small-grain cereals, effective long-term weed management in low external input and organic systems can only be achieved by tackling the problem in a wider context, i.e., at the cropping system level. Basic principles of this approach, examples of cover crop and intercropping use for weed suppression, and an application in a 2-yr rotation are presented and discussed.

Nomenclature: Barley, *Hordeum vulgare* L.; carrot, *Daucus carota* L.; corn, *Zea mays* L.; leek, *Allium porrum* L.; onion, *Allium cepa* L.; sugar beet, *Beta vulgaris* L.; wheat, *Triticum aestivum* L.

Key words: Mechanical weed control, thermal weed control, preventive methods, organic cropping, low-input systems.

Interest in physical and cultural weed control methods has grown steadily for the past two decades in many European countries, partly as a consequence of an increasing public concern about pesticide use. Both groundwater and surface water have been unacceptably polluted in many cases because of intensive pesticide use, especially in The Netherlands and Denmark. Herbicides have often been the main reason for those contaminations (Mogensen and Spliid 1995; Spliid and Koeppen 1998), and herbicides may contribute significantly to a general impoverishment of the flora and fauna in the agricultural landscape (Marshall et al. 2003). Governmental actions have been taken in countries such as Denmark, Sweden, and The Netherlands to impose legislative directives to cut use and emission of pesticides with the aim to limit negative effects of pesticides on the environment and to reduce human intake of pesticide residues through food and drinking water (Lotz et al. 2002; Thonke 1991). In Italy, serious groundwater pollution events occurred in the late 1980s and resulted in the definitive ban of atrazine use from crop production (Zanin et al. 1993).

Parallel to the more restricted pesticide policy, an increasing conversion to organic farming took place during the 1990s, favorably subsidized by some European countries. For example, the certified organic area in Denmark increased almost 15-fold from 1990 to 2001, covering 6.5% of the total cropped area in 2001 (Plantedirektoratet—available www.plantedir.dk). In Italy, the organically managed land increased from 71,000 to 1,200,000 ha (ca. 8.2% of total agricultural land use) in the period 1993–2001, whereas the number of organic farms increased 15-fold, from 4,200 to 63,200 (BioBank—available www.biobank.it).

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 nonchemical methods for horticultural and agricultural crops than those 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) organized under the European Weed Research Society. The group's main activity is its workshops held at 2- to 3-yr intervals (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, whereas others are old principles that have been subjected to new research. Soon, it became evident that none of them could act as a stand-alone treatment but had to be supplemented by other methods and tactics to achieve sufficient control (Melander 1998a; Rasmussen 1993). Preventive and cultural methods were thus included in the research with a particular interest for their interactions with direct methods. Preventive methods are those used before crop establishment whose main goal is to reduce weed emergence in the crop (e.g., crop sequence choice, primary tillage, stale-seedbed technique, use of cover or smother crops). In contrast, the main goal of cultural methods is to reduce weed competition through the enhancement of crop competitive ability, e.g., through the use of competitive crop genotypes, transplants, and appropriate sowing or planting pattern and fertilization strategy (Bàrberi 2002). In recent years, advanced technology, such as digital image processing for automatic steering systems for steerage hoes and global positioning system for electronic mapping of crop seed positions for subsequent guidance of selective weeding devices, has moved into the area and opened up new perspectives for physical weed control (Melander 2004).

Others have formerly reviewed the developments in nonchemical weed control methods (Bond and Grundy 2001; Parish 1990; Rasmussen and Ascard 1995). This article includes the most recent work and focuses especially on examples of physical control methods against annual weeds in row crops and small-grain cereals and how relevant preventive and cultural methods can be integrated with physical methods to improve overall weed control and crop yield. And finally, the relevance of implementing multiple tactics in herbicide-free crop rotations to achieve a cropping system–based weed management approach is presented and discussed.

Row Crops

The Weed Problem

Vegetables and sugar beets are row crops that normally require a high level of weed control to avoid significant yield losses and reductions in quality from weed competition, to ease harvest operations, and to avoid weed seed dispersal promoting the buildup of future weed populations. Although most row crops generally have low competitive abilities against weeds, there are differences that may determine the weed control level needed as well as the critical period during which a certain level of weed control is required. Row crops, such as carrots, cabbage (*Brassica oleracea* L.), and sugar beets, that reach canopy closure can suppress late-emerging weeds typically from mid-season and onward in contrast to crops that never reach canopy closure, such as direct-sown onion and leek (Baumann et al. 1993). The latter crops require almost complete weed control over the entire growing season and are therefore the most demanding crops, technically and economically, to maintain weed free. Hand-weeding intrarow weeds, i.e., those growing between the crop plants in the rows, is an appreciable financial burden in organic crop production systems and where herbicide effectiveness is insufficient in conventional cropping systems. Time consumption for hand-weeding varies according to weed density and the success of preceding weed control measures but typical figures are up to 150 h ha^{-1} in sugar beets (Ascard et al. 1995a) and 100 to 400 h ha^{-1} in carrot and drilled leek and onion (Ascard 1990; Melander and Rasmussen 2001; J. Ascard and F. Fogelberg, unpublished data). Time consumption in onion may even reach 600 h ha^{-1} after poor weed control in weedy fields (J. Ascard and F. Fogelberg, unpublished data). In contrast, transplanting followed by careful cultivation can lower time consumption to 10 to 50 h ha^{-1} as observed in transplanted onion and sugar beets (J. Ascard and F. Fogelberg, unpublished data; Melander 2000). Mechanization of the intrarow weed control would not only lower the direct costs for hand-weeding but also release time and labor to be used elsewhere in the production. In many parts of Northern Europe, where it might be difficult to find enough labor for hand-weeding, mechanized physical intrarow weed control could enhance the possibilities for growing more profitable organic vegetables and thereby improving growers' income (Melander 1998b).

Direct Methods

Row crops are typically grown at 300- to 700-mm row spacing and present two different situations for direct physical weed control of entirely different difficulty. Interrow weeds can be removed by ordinary interrow cultivation relatively easily although intrarow weeds constitute a major challenge.

Interrow Control

Mechanical methods that only work the interrow space usually work successfully in most situations, mainly because the crop plants are not directly affected by the weeding tools and moreover can be shielded in different ways (Mattsson et al. 1990). Interrow cultivation is regularly used both in conventional and organic row crops and has in many cases replaced chemical weed control in conventional winter canola (*Brassica napus* L.) in Denmark. Ordinary steerage hoes with hoe blades configured either as a "ducks foot" or "A-width" shape (Melander et al. 2003) mounted on either S-tines or shanks are normally used for interrow cultivation, but other cultivators such as rotary hoes, rolling cultivators, and power take-off (PTO)-driven cultivators are also used (Bowman 1997). Several new implements have been introduced recently where multiple mechanical tactics have been included to improve effectiveness. For example, Weber (1997) combined the weeding mechanism of a hoe blade with that of a PTO-driven rotary steel brush. The hoe blade loosens and uproots the weed plants, which are then further uprooted and laid bare on the soil surface by the steel brush. Such a setup has improved weeding effectiveness under more unfavorable weather conditions and/or when the weeds have become large.

Manual steering has been the common method for decades to keep the interrow 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 (Søgaard and Olsen 2003; Tillett et al. 2002) and are capable of steering hoes and other implements automatically along a crop row (Wiltshire et al. 2003). 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 $\pm$ 15 mm deviation from a center 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 (Søgaard et al. 2002).

Intrarow Control

Flaming before crop emergence has been the predominant thermal weed control method in slow-germinating row crops such as onion, leek, carrot, and corn. Preemergence flaming is only of limited value in fast emerging crops such as kale (*B. oleracea* L. var. *acephala* DC. subvar. *laciniata* L.) because the crop may easily emerge before most weeds, making flaming useless (Melander 1998a). There are two fundamental types of thermal weeders on the market: the covered flamer, flaming to 1,900 C, or the infrared weeder, with essentially no visible flame and heating to 900 C (Ascard 1998; Laguë et al. 2001). 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 (Ascard 1998; Lampkin 1997). Flaming kills weeds that have emerged before the crop, mainly by rupturing the cell membranes and the indirect effect of subsequent desiccation (Bertram 1994; Ellwanger et al. 1973a, 1973b). The effect of flame weeding varies with plant size (Ascard 1994a, 1995, 1998); plants at 4 to 12 leaves required two- to fourfold higher energy rates for control than those at the zero- to four-leaf stage.

Mobile soil steaming has acquired additional attention recently because of its potentially very high effectiveness leading to almost complete weed control for 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 150 mm depth (Peruzzi et al. 2002). Experiments carried out in Italy showed that addition of KOH at 4,000 kg ha^{-1} reduced the total weed seedbank by 76% compared with 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 (Pinel et al. 1999). This has lead to the idea of band-steaming where only a limited soil volume is steamed corresponding to the intrarow area (Melander et al. 2002). Band-steaming is currently under investigation and more results are required to judge the potential for practical use.

Several mechanical methods have application for intrarow weed control, primarily controlling weeds by uprooting or burying, or both (Kurstjens and Kropff 2001; Kurstjens and Perdok 2000; Terpstra and Kouwenhoven 1981). As with most other mechanical weeding implements, operator skill, experience, and knowledge are critical to success. Drawbacks to mechanical intrarow 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 (Lampkin 1997), but the spring-tine harrow with flexible tines is probably the most preferred one with the widest range of applications (Bàrberi et al. 2000). It can either be used before crop emergence or postemergence, and it involves weeding the whole crop. Torsion weeders, with pairs of tines set on either side of the crop row and lowered 20 to 30 mm into the soil (Bowman 1997), offer more precise intrarow 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 intrarow weed control (Bowman 1997). 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 1990s (Melander 1997). The torsion weeder, finger weeder, and brush weeder are all mainly developed for postemergence use in high-value vegetable crops because of their low working capacity. However, their application for sugar beets including weed harrowing have been studied in a series of experiments in southern Sweden, and the torsion weeder generally performed better than the other three methods both in terms of weeding and cost effectiveness (Ascard et al. 1995b), but the weed harrow had higher work rates and required no particular attention on steering. Attempts are now made to use new technology to guide weeding tools to selectively remove the weeds without touching the crop plants (Blasco et al. 2002; Bontsema et al. 1998; Søgaard and Heisel 2002). Precision guidance of physical postemergence intrarow weeding, or robotic weeding, is still in its infancy, and no equipment is operating on a commercial basis yet.

Results with mechanical weed control have been particularly good in transplanted row crops such as cabbage, celery (*Apium graveolens* L.), leek, onion, and sugar beet (J. Ascard and F. Fogelberg, unpublished data; Melander 2000; Melander et al. 1999), where transplanting itself creates very favorable 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 effect 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 with 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.

Mechanical intrarow methods generally operate with low selectivity, especially in drilled row crops having slow emergence and low initial growth rates, such as carrots, onion, and leek. The same applies to crops like sugar beets and silage corn under cool North European growing conditions where cool and wet weather may often slow down crop growth in the beginning of the season. 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, as illustrated in Figure 1 (also shown

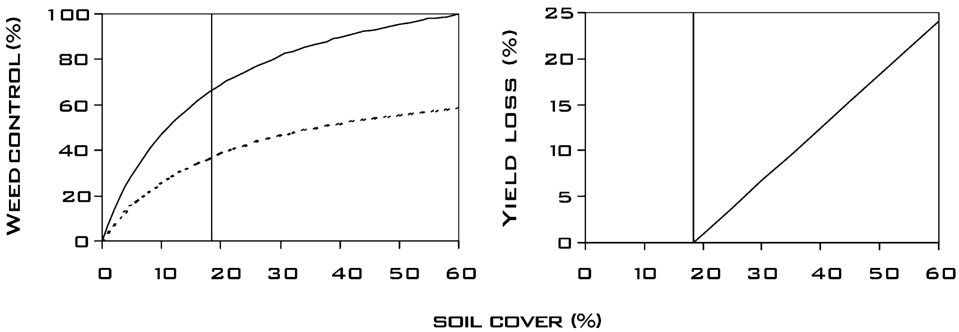

FIGURE 1. Curves showing the selectivity of brush weeding in direct-sown onions at the two-leaf growth stage (12 to 14 cm tall). The left graph shows the relationship between control of wild mustard (*Sinapis arvensis* L.) at the zero- to two-true leaves stage (solid line) and at the two- to four-true leaves stage (dotted line) and soil cover of aboveground foliage of onions. The right graph shows the relationship between marketable yield of the same onions and soil cover. The vertical line in both graphs show the crop soil cover at which significant crop injuries began to appear. Crop soil cover expresses the intensity of brush weeding; high coverage means high intensity. (Modified from Melander 1997).

by Kurstjens and Bleeker, 2000). It is essential that the crop has a size advantage over the weeds when implement settings cause the weeding tools to affect the crop plants directly, which may be necessary to achieve sufficient control. For example, sugar beets need to have developed four to six true leaves (Ascard and Bellinder 1996; Ascard et al. 1995b) and drilled onions a height of more than 10 cm (Ascard and Bellinder 1996; Melander and Hartvig 1995) before they can tolerate direct contact with mechanical weeders.

Combinations of Direct Intrarow Methods

Mechanical postemergence methods have to be combined with methods applied preemergence 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. Preemergence 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. Baumann (1992) achieved 90% weed control in corn on a sandy soil by combining two passes of preemergence weed harrowing with eight passes of postemergence harrowing with no associated yield decline. Preemergence flaming followed by postemergence vertical brush weeding gave 90% intrarow weed control over 2 yr of experiments in leek but only 39 to 74% effectiveness in onion (Melander and Rasmussen 2001). However, Melander (1998a) obtained 85% intrarow effectiveness in onion with the same strategy in one of two experiments. 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. Time consumption for hand-weeding has been found to relate linearly to the number of intrarow weeds, and time consumption is proportionally reduced to approximately the same extent as intrarow weed numbers after physical weeding (Melander and Rasmussen 2001). Other results have indicated that the much cheaper and environmentally friendlier method of preemergence harrowing may replace flaming in onion (Melander 1998c). However, in leek, flaming has been found to secure early crop plant establishment and subsequently final yield by reducing and eliminating early-weed competition more effectively than harrowing (Melander and Rasmussen 2001). The stronger effect of flaming in leek than in onion is probably the result of the later sowing of leek, when soil temperatures are normally higher, allowing more weeds to emerge before flaming. Of the postemergence methods studied for leek and onion, hoeing close to the row may be as good as brush weeding (Melander and Hartvig 1997; Melander and Rasmussen 2001). From an economic point of view, harrowing and hoeing are more feasible than brush weeding both in terms of investment and use (Melander 1998b).

Interactions with Preventive and Cultural Methods

Preventive and cultural methods are regarded as measures that may improve the outcome of physical intrarow 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. However, whether these methods really add such positive effects to physical weed control strategies in row crops have not been unambiguously proven in the relatively few studies made on this subject.

A stale seedbed, defined as a seedbed prepared several days, weeks, or even months before transplanting or drilling a crop (Johnson and Mullinix 1995), can decrease weed numbers considerably in the succeeding crop (Leblanc and Cloutier 1996; Rasmussen 2003). Stale seedbed is commonly used in practice before transplanting and late sowing of row crops (Melander et al. 1999). However, results vary according to the prevailing weather conditions (Melander 1998c; Rasmussen 2003; Van der Weide et al. 2002), and soil moisture content appears to be the major factor determining the efficacy of a stale seedbed (Bond and Baker 1990; Roberts and Potter 1980). A stale seedbed may even worsen the weed problem of some weed species (Van der Weide et al. 2002), and deliberately delaying the sowing of some crops can be detrimental to the yield as observed for onion (Melander 1998c) and fodder beet (*Beta vulgaris* L.) (Rasmussen 2003). However, a possible negative yield effect should be counterbalanced against the reductions in cost for manual weeding, which may even be larger than a potential yield loss.

Soil cultivation in darkness prevents weed seeds from being exposed to daylight that breaks the dormancy of light-sensitive weed seeds placed below the soil surface before cultivation. Fogelberg (1999) and Melander (1998a) studied this tillage tactic in combination with direct physical methods in vegetables and got variable results. In 1 yr, seedbed preparation and drilling in darkness reduced weed emergence by more than 50% and when adding the effect of vertical brush weeding, intrarow weed numbers were reduced by 90% in onion and 84% in kale (Melander 1998a). Inexplicably, no effects of seedbed preparation and drilling in darkness were observed the next year. Fogelberg (1999) found only small effects of seedbed preparation and drilling in darkness and after vertical brush weeding, there was little difference between crop establishment undertaken in darkness or daylight. The great variation in the effect of night time soil cultivation, likely related to variation in seed dormancy status at the population and community level, also have been observed in other studies (Ascard 1994b; Jensen 1992), and there is still no clear understanding as to how this measure should be used to achieve the desired effects more regularly.

Melander and Rasmussen (2001) combined seed priming, slurry placement, and variety choice (only leek) with physical preemergence and postemergence methods in leek and onion to study their interactions. Generally, the cultural methods had no significant influence on the effects of physical weeding in terms of their effect against intrarow weeds. They also appeared not to affect the tolerance or robustness of the crop plants against negative effect from the physical methods. However, seed priming and variety choice generally did improve final marketable yield in the leek experiments and seed priming also did so in the one experiment with onion. Moreover, seed priming hastened the date of leek seedling emergence and promoted early leek growth, which may indicate a higher crop competitiveness or tolerance to weeds, although this was not detectable from the experimental data. More competitive row crops reaching canopy closure would presumably respond more markedly to cultural methods enhancing crop growth. Row crops, such as cabbage, sugar beets, and carrots, could become more competitive against weeds that survive physical weeding if their growth was enhanced by better timing and access to nutrients. This could mean that one or two physical treatments might be saved or the threshold for applying weed control might be raised. The choice of a more competitive crop variety is another example of a cultural measure that could improve the outcome of nonchemical weed control. Balsari et al. (1994) noted that a vigorous cabbage variety suppressed weed growth more effectively than some other varieties. Breeding programes for vegetables should take this aspect into consideration and identify variety of characteristics that could improve competitiveness against weeds.

Small-grain Cereals

The Weed Problem

Small-grain cereals germinate and emerge fast and are usually much more competitive than row crops. In most cases, weed control is carried out to reduce yield and quality loss and harvest problems. However, in some cases weed control is mainly targeted at preventing weed seed production and subsequent seed shedding that could otherwise increase weed problems in other crops in the rotation. In this presentation, the main emphasis is on the implementation of physical, preventive, and cultural weed control methods in cereals in organic farming. Some examples of integration of physical (Blair and Green 1993; Blair et al. 1997) or cultural (Christensen et al. 1996) methods with herbicide use have been presented earlier. For example, Cirujeda et al. (2003b) found that weed harrowing could be an effective weed control measure against herbicide-resistant corn poppy (*Papaver rhoeas* L.). Cheap and efficient herbicides are available for conventional farmers against most weeds, and the nonchemical methods cannot compete with them in terms of weed control, yield gain, economics, and ease of application.

Direct Methods

Small-grain cereals are usually grown at high densities (> 300 plants m^{-2}) at 100- to 120-mm row spacing. Presently, in organic farming, the most used direct weed control methods are mechanical weed control: weed harrowing and interrow hoeing. Weed harrowing treats the whole crop, whereas interrow hoeing is located mainly to control weeds in the interrow area.

Weed Harrowing

In broadcast-sown crops, control can be conducted using a spring-tine harrow or other harrow types. If the crop plants are larger than the weeds, the weeds will be damaged more by the harrow (Kurstjens et al. 2000; Rasmussen and Ascard 1995). Crops have different sensitivity to disturbance; monocotyledons such as cereals are less sensitive than dicotyledons, and high crop density in the rows causes the tines to move away from the rows, thereby making the control selective (Rasmussen and Ascard 1995).

Preemergence soil cultivation after crop sowing and before the crop emerges has the potential to control early-germinating weeds (Rasmussen 1996). At the same time, it may create weed problems by stimulating subsequent weed germination (Kees 1962). Even if preemergence soil cultivations only provide small reductions of weed density, the competitive ability of the weeds may be reduced significantly (Melander and Hartvig 1995). Preemergence soil cultivation may also increase the effectiveness of subsequent cultivation because late-germinated weeds that emerge after cultivation are smaller than early-germinated weeds at the time of the next cultivation (Buhler et al. 1992).

Early postemergence harrowing in the early growth stages of the crop may be accompanied by serious covering of the crop with soil (Rasmussen 1990), which can cause yield loss. It is important to match the intensity of weed control to the need because at a certain point of intensity, crop injury will overshadow the effect of weed control as the intensity of soil cultivation is further increased (Figure 2) (Rasmussen 1991). Increasing the number of harrowings increased the percentage of weed control, as well as the percentage of soil covering of the crop in spring barley, and the increasing levels of weed control resulted in decreasing yields (Rasmussen 1991). Rasmussen (1998) found a yield depression in two of three experiments as a result of early postemergence weed harrowing in winter wheat in the fall, whereas harrowing in spring was less detrimental. However, tap-rooted species with an erect growth habit, such as scentless mayweed (*Tripleurospermum inodorum* L.), corn poppy, and vol-

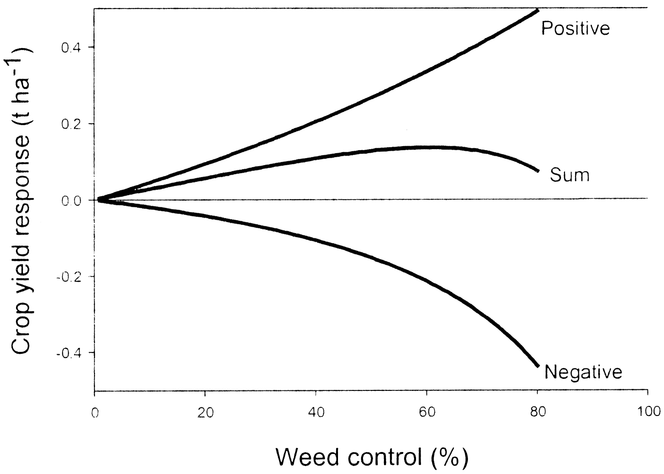

FIGURE 2. The principles of the relationship between weed control and yield loss in cereals by postemergence weed harrowing. "Positive" is the effect of removing the weeds on the cereal yield. "Negative" is the detrimental effect of the weed control on the cereal yield. "Sum" is the total result. (Simulation based on equation 11b in Rasmussen 1991).

unteer canola, are poorly controlled by weed harrowing in spring in winter cereals, in contrast to shallow and weakly rooted weed species with prostrate growth habits (e.g., common chickweed [*Stellaria media* (L.) Vill.] and birdeye speedwell [*Veronica persica* Poir.]) (Rasmussen 1998; Welsh et al. 1996; Wilson et al. 1993). The tap-rooted species are more easily controlled at their early growth stages in autumn when they are less well rooted but possible negative effects on the crop make the fall harrowing risky.

Selective harrowing is possible after tillering because the tines then operate only in the interrow spaces. As the crop grows taller, the rows offer increasing resistance to the tines, and the rows force the tines to cultivate the interrow spaces (Rasmussen and Svenningsen 1995). Spring-tine harrows can be used at later growth stages than other types of harrows. Rasmussen and Svenningsen (1995) showed that selective harrowing could operate with high selectivity, so that high weed control can be obtained without significant crop injuries. No detectable crop damage was found as a result of selective harrowing in winter wheat in spring. Late harrowings where tines only cultivate the interrow spaces cannot be expected to control well-anchored tap-rooted weed species with an erect growth habit and especially not those growing in the rows.

Interrow Hoeing

Interrow hoeing using ducksfoot or "A"-width hoe blades that cultivate the interrow area of cereals has been found to control tap-rooted and erect weed species more effectively than harrowing (Johansson 1998; Melander et al. 2001, 2003; Rasmussen and Pedersen 1990). Interrow hoeing is also less sensitive to treatment timing because even well-anchored weeds can be uprooted (Melander et al. 2003). Hoeing is a highly selective control method, and results are not greatly affected by soil moisture and soil type (Rasmussen and Ascard 1995). Thus, interrow hoeing can be postponed to spring in winter wheat, where the crop is less vulnerable, without lowering the effectiveness against the weeds. However, accurate steering is essential to avoid severe crop damage, and to reduce the steering task a row spacing of 200 to 240 mm is recommended (Melander et al. 2001; Rasmussen and Pedersen 1990). Manual steering is common, but the new electronic steering systems that automatically steer the hoe seem to have potential even for row hoeing in cereals (Tillett et al. 1999), and this could increase the working capacity and thereby lower the operational costs. According to Melander et al. (2003), driving speed had no influence on crop yield or the weeding effect of interrow hoeing, despite the increasing soil coverage of crop plants that followed early interrow hoeing with increasing speed.

Widening crop row spacing to allow for interrow hoeing may reduce yield. However, evidence on the effect of row spacing on yield is inconclusive in winter as well as spring cereals, as is the knowledge about the effect of row hoeing on yield. Andersson (1983) showed that when row spacing of winter wheat was increased from 100 to 220 mm with the same seeding rate, the largest yield was achieved with 100-mm row spacing, and for every millimeter increase of row distance, yield was decreased by 0.07%. Yield losses of 4 to 12% have been reported for winter cereals and spring barley when changing spacing from 100 to 120 mm to 200 to 240 mm (Johansson 1998; Melander et al. 2001; Mülle and Heege 1981; Rasmussen and Pedersen 1990). In contrast, changing crop row arrangement did not have a major effect on winter wheat yield when the row spacing was increased from 125 to 330 mm (Blair et al. 1997). Rasmussen (1998) found no yield reduction from increasing row spacing of winter wheat from 120 to 200 mm, and Tillett et al. (1999) found no yield reduction in the same crop at row spacing up to 220 mm. In Finnish experiments with spring barley, increasing the spacing between rows from 125 to 250 mm decreased yield by 12 to 13%, and interrow hoeing did not increase the yield further. Interrow hoeing was more effective than weed harrowing or rotary hoeing with only a slight yield decrease because of mechanical effect (Lötjönen and Mikkola 2000). In contrast, Mertens and Jansen (2002) found no yield reductions in spring wheat grown at 300-mm row spacing where interrow hoeing and weed harrowing were conducted compared with spring wheat grown at 100-mm row spacing with only weed harrowing.

Combinations of Direct Methods

Interrow hoeing controls weeds growing in the interrow area almost completely under favorable circumstances, whereas those growing in the intrarow area are only partly controlled (Johansson 1998). The effect on intrarow weeds depends on both the amount of soil coverage caused by hoeing (Pullen and Cowell 1997) and the suppressive ability of the crop. Johansson (1998) equipped the hoe with rear-mounted ridging tools to increase soil covering of intrarow weeds in spring barley and improved weed control by 10 to 20%. Melander et al. (2001) achieved 30% more weed control (averaging the effect on inter- and intrarow weeds) in winter barley and winter rye (*Secale cereale* L.) when weed harrowing followed hoeing immediately. The combination of interrow hoeing with weed harrowing also gave good effect on intrarow weeds in winter wheat (Cirujeda et al. 2003a). Combination of interrow hoeing and weed harrowing at 240-mm row width gave better weed control in winter wheat than harrowing alone at 120-mm spacing (Rasmussen 2004), and Ruhe (2000) also found the combination of hoeing and harrowing more effective against weeds than harrowing alone.

Interactions with Preventive and Cultural Methods

Preventive and cultural factors are applied to improve the effect of mechanical weed control, i.e., weed harrowing or interrow hoeing. The aim is to improve the weed control effects, improve the crop tolerance to mechanical weed control (that is, change the selectivity in favor of the crop), and to improve crop competitiveness against weeds that have escaped mechanical control.

Improving Weed Control Effects

The efficacy of weed control will not be directly improved by factors that reduce weed density in the crop. However, using methods that reduce weed density will result in even lower weed density after treatment, compared with if these methods were not used, provided the same efficacy is achieved. Stale seedbed (Oliphant 1977), delayed sowing (Christensen et al. 1996; Rasmussen 2004), and tillage in darkness (Welsh et al. 1999) are examples of factors that aim at this effect.

Improving Crop Tolerance

Little is known about whether different crop cultivars have different tolerance to mechanical weed control, and there are few ways of changing the selectivity. One is to manipulate the crop so that it emerges earlier than the weeds, either by using crop seeds that have high vigor (K. Rasmussen and J. Rasmussen 2000) or by using tillage in darkness, which can delay as well as reduce the emergence of some weed species (Jensen 1995).

Improving Crop Competitiveness Against Remaining Weeds

Giving crops better access to nutrients than weeds augments crop competitiveness. Because most annual weeds germinate from the top few millimeters of the soil (Lampkin 1997), nutrients broadcast on the top of the soil, or worked into the top 50 mm, will give the weeds equal opportunity to use these nutrients together with the crop. Placement of nitrogen, 10 to 50 mm from the row and 50 mm deep in the soil, may improve early nitrogen uptake and crop growth; thus, the crop gains an initial competitive advantage over weeds (Petersen 2001; Petersen and Mortensen 2002), and this may result in up to 50% reduction in weed biomass (Rasmussen et al. 2000). Placement of mineral fertilizer and injection or placement of slurry into the soil at the time of sowing of spring-sown cereals could improve crop competitiveness, effectiveness of weed harrowing (and of chemical control), and crop yield (Rasmussen 2002; Rasmussen et al. 1996). Placement of fertilizer in spring at approximately 60-mm soil depth and approximately 70 mm from the crop row improved early crop growth more than that of the weeds in winter rye and winter barley, thus improving the crop's competitiveness with weeds compared with applying fertilizer on the soil surface (Melander et al. 2001). In winter wheat, this was only true for shallow-rooted weeds such as common chickweed, whereas growth of tap-rooted weeds was enhanced (Melander et al. 2003). Placement of fertilizer for winter cereals improved the weeding effect of interrow hoeing combined with weed harrowing, especially when also combined with increased crop density (Melander et al. 2001).

Cereal varieties with a taller canopy (Grundy and Froud-Williams 1997), faster growth rate, or denser canopy may reduce weed biomass by as much as 25% (Rasmussen et al. 2000). Attributes such as early- and deep-rooting pattern (Rasmussen 2002), early vigor, larger leaf size, and allelopathic ability further increase cultivar competitiveness (Bond and Grundy 2001). Christensen et al. (1994) found significant effects of winter wheat variety on weed density and biomass, and Didon (2002) identified significant differences in the suppressive ability against weeds of barley varieties. Hansen (2002) has developed a competition index for winter wheat and spring barley varieties on the basis of final height, leaf-area index, and early growth.

Crop plants that emerge earlier than weed plants have an advantage in competition, whereas the opposite is true, if the weeds emerge first (K. Rasmussen and J. Rasmussen 2000), and this can aid the effect of mechanical weed control. The seedbed or planting bed should be made for the best establishment of the specific crop, and crop seeds with high vigor should be used.

Higher crop density results in better competitiveness of the crop. Crops planted in rows allow for weeds to use the light between the rows, whereas crops that are uniformly distributed are better at competing with the weeds, resulting in a 30% decrease in weed biomass (Weiner et al. 2001). Christensen et al. (1994) found that increased winter wheat density decreased weed density and biomass but only when planted at more than 300 plants m^{-2}. Grundy and Froud-Williams (1997) found that increased crop density decreased weed biomass by the end of the growing season.

As mentioned previously, intrarow hoeing only controls intrarow weeds partially by soil thrown into the row, and by suppression from the cereal plants in the row. Enhancing crop competitiveness against surviving or partly controlled intrarow weeds is important to further improve the weeding effect. Doubling crop plant density in the row at 240-mm row spacing from the density commonly used at 120-mm row spacing, using the same seeding rate per hectare at both spacing, can increase intrarow weed suppression in spring barley and winter wheat, as shown by Rasmussen and Pedersen (1990). Melander et al. (2001) showed that further increasing crop density by 60% compared with the doubled density in the rows at 240-mm row spacing reduced weed biomass by 34% (relative to the weed biomass at double plant density). In addition, the combination of increased crop density and fertilizer placement with interrow hoeing and weed harrowing at 240-mm row width in winter cereals improved weed control efficacy almost to the same level as herbicide efficacy.

Weed Management at the Cropping System Level

Although integration of preventive and cultural methods with direct methods often improves weed control in row crops and small-grain cereals, effective long-term weed management in low external input and organic systems can only be achieved by tackling the problem in a wider context, i.e., at the cropping system level. This approach takes into account the systemic nature of agroecosystems (Ikerd 1993), which, for example, has been deemed important for devising effective organic crop production systems (Andrews et al. 1990; Lockeretz 2000). In such systems, a reductionistic view on weed management (e.g., a focus only on direct weed control methods) is highly questionable because it underestimates the interactions among system components and their carryover effects across growing seasons. An example of this is the slower nutrient release from organic amendments and fertilizers compared with synthetic fertilizers, which results in (1) delayed weed emergence, which shifts the timing of crop–weed competition for nutrients (especially nitrogen) to later in the crop cycle with carryover effects into the subsequent growing season(s) and (2) altered weed community dynamics with effects varying with weed species, organic fertilizer source and its treatment, and environmental conditions (Bastiaans and Drenth 1999; Grundy et al. 1998; Liebman and Davis 2000; McCloskey et al. 1996). Similarly, compared with herbicides, physical weed control has a reduced persistence of effect and may stimulate weed emergence (Becker and Böhrnsen 1994).

As a consequence, it seems correct that weed management in crop production systems in which use of agrochemicals (synthetic fertilizers, pesticides, and herbicides) is scant or nil should be tackled by taking into account interactions among system components and agronomic practices that occur both in the present crop, in subsequent crops, and in-between cropping phases, i.e., at the cropping system level (Bàrberi 2002).

Basic Principles

In this context, weed management is based on optimum cropping system planning, with maximum diversification of the cropping system (crops and related cultural practices) as the crucial point. Where environmental or economic conditions are not constraining, alternating winter and summer crops, grain and root crops, nutrient depleting and nutrient building crops, and introducing a ley phase or cover crops can achieve this. All these tactics prevent the establishment of a specialized and highly competitive weed community (Buhler 1999). Crop rotations should be replaced by flexible crop sequences to reduce the risk of weed adaptation to a given cropping system (Bàrberi 2002).

Obviously, diversification of the crop sequence automatically results in diversified primary tillage and type and timing of seedbed preparation and cultivation, depending on the needs of the different crops. Reduced weed emergence consequent to cropping system diversification has been proven to determine long-term weed management effectiveness in organic systems in the U.K. (Welsh et al. 1999).

Cover Crops

Cover crops are non–cash crops that can be grown before or together with a cash crop with the purpose of keeping the soil covered with vegetation as long as possible throughout the year. When grown before the main crop, cover crops can be either ploughed under or crushed, treated with glyphosate, and left on soil surface ("dead mulch"); in the latter case, the subsequent cash crop is directly drilled through the mulch. When grown together with the cash crop, cover crops are referred to as "living mulches." Because of a wealth of beneficial effects on the agroecosystem (e.g., conservation of soil fertility and moisture, activation of soil nutrient dynamics; regulation of pest, pathogen and weed populations), cover crops represent an important management tactic for ecological agricultural systems, the optimized use of which can be crucial for the success of these systems. Cover crop effects on weeds vary depending on cover crop and weed species and on management (Bàrberi and Mazzoncini 2001). Recent research on cover crops in Europe has been conducted in both Mediterranean and more northern environments. Successful weed control by cover crops can even be achieved under harsh Scandinavian conditions (Brandsæter and Netland 1999; Hall et al. 2004), although it seems a more promising tool in more temperate climates. For example, Moonen and Bàrberi (2004) observed a 25% reduction in total weed seedbank density 7 yr after the introduction of a rye cover crop in a plough-based (PB) corn system compared with the non–cover cropped system. In the no-till (NT)–based corn system, however, the more suppressive cover crop was subterranean clover (*Trifolium subterraneum* L.), with a 22% reduction on average. Differences in weed species composition and total seedbank density (ca. fivefold in NT than in PB) were mainly related to tillage system rather than to cover crop species. These results show that not all cover crop and management system combinations are capable of decreasing weed pressure, thus the actual weed control effectiveness of cropping system diversification elements (cover crops, in this case) must always be tested in a practical context.

Brassicaceae cover crops can also exert a weed-suppressive effect, thanks to the release of isothiocyanates from glucosinolates after destruction of plant tissues (Angelini et al. 1998). This effect, which can also negatively affect soil-borne pathogens and nematodes, is often referred to as biofumigation (Kirkegaard and Matthiessen 2004). Weed control is enhanced when plant tissues are crushed and squeezed (e.g., when a rotary harrow is equipped with hammerlike tools rather than with blades) and immediately incorporated in soil (Matthiessen 2004). Weed suppression also depends on species and cultivar and on application method of the biofumigant. For example, white mustard (*Sinapis alba* L.) is more suppressive than Indian mustard [*Brassica juncea* (L.) Czern.], but some varieties of the latter have enhanced suppression compared with others (Brown et al. 2004). Similarly, application of defatted seed meals is usually more effective than incorporation of fresh green manure tissues (Boydston et al. 2004; Brown et al. 2004). A variant of biofumigation is the so-called biodisinfestation, where an air-proof plastic film covers soil in which green manures are incorporated to stimulate production of toxic compounds under anaerobic conditions. Biodisinfestation is currently under investigation in The Netherlands for application in high-value vegetables and flower production (Lamers et al. 2004), but its weed control potential is still unknown. Although promising, the use of allelopathic cover crops or green manures in European crop production systems is still in its infancy because a lot of basic and applied knowledge (e.g., on how to boost the effect under field conditions) is still lacking and is of limited interest to industry (Zanin and Catizone 2003).

Intercropping

Compared with living mulches, in intercropping, the species (usually two) grown simultaneously are all cash crops. Similar to cover crops, intercrops can improve use of natural resources by the canopy and subtract them from the weeds (Liebman and Dyck 1993). Besides this, use of intercrops (e.g., in organic systems) is usually more accepted by farmers than use of living mulches just because all components produce a marketable yield. Baumann et al. (2000) showed that a leek–celery intercrop sown in a row-by-row replacement design decreased relative soil cover of weeds by 41% and reduced common ragwort (*Senecio vulgaris* L.) density and biomass in particular by 58 and 98%, respectively, compared with leek and celery sole crops, mainly because of decreased light transmittance through the canopy. The intercrop also increased yield by 10% compared with sole crops. Other examples of increased weed suppression and yield achieved with intercropping under European conditions refer to cereal–pulse combinations (Bulson et al. 1990; Haymes and Lee 1999; Paolini et al. 1993).

An Example of Weed Management at the Cropping System Level

According to the concept of cropping system–based weed management, weed management strategies need to be integrated into cropping system management by applying agroecological knowledge. An example of what we consider to be a cropping system level approach to weed management can be found in the work of Melander and Rasmussen (2000), which deals with a 2-yr rotation between a cereal and a row crop (sugar beet or a vegetable crop). This weed management system has the purpose to deplete the weed seedbank in the year when the highly competitive crop (i.e., the cereal) is grown to reduce weed emergence in the row in the poorly competitive row crop in the subsequent season. Winter wheat or spring barley is grown in the first year leaving 250-mm-wide open bands between rows, which are repeatedly hoed to stimulate weed emergence, basically applying the concept of the stale-seedbed technique. In the next season, sugar beet or a vegetable crop is direct-drilled in the bands. Minimal soil disturbance in the second year prevents bringing up weed seeds from lower soil depths. Compared with the standard system, total weed emergence in the second year was reduced by 81 to 92% after spring barley in the first year provided that weed seed shedding onto the bands was effectively prevented. In contrast, no noticeable benefit was observed after winter wheat in the first year, possibly because of the mismatch between growing periods of crop and dominant weeds (winter vs. spring, respectively). This system can be applied either to integrated or organic production, where decreased intrarow weed emergence in the second year can significantly cut down costs of hand-weeding.

Although this system does not take into account all management practices (i.e., fertilization management), its success relies on the fact that tactics are deployed at the cropping system level rather than at crop level by integrating crop sequence, soil tillage, and direct weed control measures. This system should be improved by reducing weed seed shedding in the noncropped bands and control of perennial weeds in the second year, when no primary tillage is performed. The cropping system presented in this study demonstrates how complementary crops in a rotation sequence may be made even more so by taking advantage of differences in crop spatial arrangement and tillage practices between rotation phases.

Conclusions

Research has added considerable knowledge and understanding of the features of direct weed control methods in row crops and small-grain cereals in recent years. However, improvements are still needed to lower costs, increase reliability in terms of weeding effectiveness and crop tolerance, and to ease operation of the implements. New techniques and ideas are regularly emerging, and advanced technology may have the potential to radically improve the methods and probably make them relevant for wider usage in conventional cropping also.

However, examples of cropping system–based approaches to weed management in organic farming and low external input systems are still not common in the international scientific literature. This is probably dependent on the conflict between the need for implementing long-term research, which is particularly important in organic farming, and short-term research funding (Lockeretz 2000). In addition, researchers are often reluctant to undertake long-term studies because of methodology difficulties. Modeling crop–weed interactions and weed population dynamics might help reduce the need of on-field research, but validation of model outputs with results of ongoing long-term field experiments will still be necessary.

It should be pointed out that "reductionist" and cropping system–based research are not contrasting but complementary. As such, weed management in low external input and organic farming systems should be based on two subsequent steps: (1) adjustment of the cropping system to reduce weed emergence and abundance of troublesome species (cropping system–based step) and (2) adjustment of direct weed control methods (harrowing, hoeing, brushing, flame weeding, etc.) within the cropping system (reductionist step). Given the dynamic nature of agroecosystems, even optimized weed management systems would require some readjustment from time to time; this is another reason why long-term, cropping system–based experiments are important in integrated and especially organic farming.

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