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Precise tillage systems for enhanced non-chemical weed management

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Abstract

Soil and residue manipulation can assist weed management by killing weeds mechanically, interfering in weed lifecycles, facilitating operations and enhancing crop establishment and growth. Current tillage systems often compromise these functions, resulting in heavy reliance on herbicides, particularly in no-till systems. Herbicides are an exhaustible resource, so new approaches to merge soil conservation and non-chemical weed management are needed. This paper broadly reviews various preventive and curative non-chemical weed management tactics. It also demonstrates how innovations can be derived from functional requirements of weed management operations, and from biological processes and weaknesses in weed's lifecycles. Mechanical weeding and enhancement of weed seed mortality are highlighted as examples. Major limitations with mechanical weeding include limited weed control in crop rows at early vulnerable crop stages, weather-dependent effectiveness, and difficulties in handling crop residues. Precise steering and depth control, improved seedbed friability and lighter tractors or controlled traffic could bring considerable improvements. To expose weed seeds to predators, position them for fatal germination, viability loss or low emergence may require completely different soil displacement patterns than those of current implements and systems. Controlled traffic and precise strip tillage offer good opportunities for implementing these weed management strategies in minimum-tillage systems.

Keywords: Mechanical weeding; Cultural control; Controlled traffic; Strip-tillage; Integrated weed management

1. Introduction

The available wide range of effective herbicides has been a key to the successful development and wide adoption of simplified, cost-saving and soil-conserving tillage systems (Lyon et al., 1996; Denton and Tyler, 2002). Herbicide reliance and non-chemical weed management have remained inferior issues in tillage research, as new herbicide development, improved application technology and herbicide-tolerant crops have strengthened the belief that new technologies will solve future weed problems (Bradley, 2002; Llewellyn et al., 2002; Tranel and Wright, 2002).

However, several developments challenge this assumption. In several countries, consumer aversion towards pesticides and their negative environmental impacts have resulted in serious governmental restrictions on herbicide availability and use in the European Union (EU) (e.g., EU Agricultural Pesticides Directive 91/414/EEC; Watts and Macfarlane, 1997). In the EU, the reduced number of registered formulations is already problematic in several minor crops (Gillott, 2001; Buffin et al., 2003). The costs to discover, develop and register a new agrochemical have increased dramatically, from 25 M€ in 1975–1980 to 200 M€ in 2000 (McDougall and Phillips, 2003). This and heavy competition in a

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saturated, shrinking herbicide market will probably sustain the declined herbicide innovation rate observed over the past decade (Kalaitzandonakes and Bjornson, 1997; Shaner, 2000). As the rapid adoption of herbicide-tolerant crops indicates great market opportunities, agrochemical companies will probably focus on developing transgenic crops that exploit current herbicides (Cobb and Kirkwood, 2000).

Despite the availability of many different products, present herbicides exploit only 15–20 different modes of action (Cobb and Kirkwood, 2000), whereas only one new target site has been commercialised in the last 20 years (Llewellyn et al., 2001; Gressel, 2003). Herbicide resistance has occurred in all known target sites, presently involving 310 weed biotypes, including 10 glyphosate-resistant weeds (Heap, 2006). The increased incidence of resistance (over 100 new resistant biotypes in the last decade; Heap, 2006) is largely attributable to the use of monocultures, reduced cultivation and persistent chemicals (Cobb and Kirkwood, 2000). Repeated use of few modes of action fosters weed resistance development and shifts in weed species composition (Shaner, 1995; Powles et al., 1997), which in turn narrows the effective range of chemical weed control options, thus increasing selection pressure further. Weed communities have shifted within 5–8 years of spraying glyphosate (Shaner, 2000; Hartzler and Owen, 2003), so that increased rates and other herbicides are required to control tolerant weeds. It is questionable whether new alternatives will become available, as compounds competitive to glyphosate are very rarely discovered (Baylis, 2000; Shaner, 2000). As the time between synthesis and sale of a new agrochemical is on average 9 years (McDougall and Phillips, 2003) or more (Fernandez-Cornejo et al., 1998), it is crucial to slow down weed species shifts and resistance development by, e.g. weed seed collection (Matthews et al., 2004), delayed sowing, increased seed rates and tillage (Cavan et al., 2000; Neve et al., 2003).

Although many scientists consider herbicide efficacy an extremely valuable (Gianessi and Sankula, 2003) and exhaustible resource that should be sustained proactively (e.g., Lyon et al., 1996; Cobb and Kirkwood, 2000; Llewellyn et al., 2001), farmers generally prefer simplified herbicide-based cropping systems and insufficiently anticipate resistance (Lemerle and Sutherland, 2000; Hartzler and Owen, 2003). The complexity and skill involved in the integration and appropriate use of multiple tactics contrast strongly with the flexibility and convenience of chemical weed control.

Most studies aiming at reducing herbicide reliance have focussed on combining herbicides with cultivation (Van der Weide et al., 1993; Mulder and Doll, 1994; Burnside et al., 1994) and weed-suppressive cover crops, residues or living mulches (Teasdale, 1996; Yenish et al., 1996; Brandsaeter and Netland, 1999) in existing tillage systems. Modifying tillage systems to facilitate adoption of a more diverse range of tactics has received little attention, but could be pivotal to the sustainability of conservation tillage.

This paper reviews the applicability of non-chemical weed management tactics in different tillage systems, clarifying the general needs for tillage system adaptation. It outlines the prospects of tillage innovations that facilitate weed management tactics, exploit weaknesses in weed life cycles and integrate non-chemical weed management with soil conservation through precise guidance and spatial diversification.

2. Applicability of non-chemical weed management tactics

2.1. Applicability as related to management systems

In tillage system design, the key issue is to maximise the number of methods (i.e., weed management tactics) that could be effectively and flexibly applied, to fit a wide range of conditions and allow for easy adaptation of weed management over time. Methods could include opportunities to (1) manage living or dead mulches, (2) carry out shallow cultivations, (3) disrupt rhizomes of perennial weeds, (4) bury weed seeds at depths from which they cannot emerge and (5) enhance crop competitiveness. Their applicability and effectiveness depend on climate, farm size, weeds, crops and management system.

A management system involves tactics that manipulate soil and residues in defined spatial management units (i.e., field, strip/zone or patch) over time. In Table 1, a method's applicability for management systems is determined by the properties of a management unit (i.e., surface flatness, soil structure, residue quality, residue amount, soil structure, crop presence) at the time of application. Management units might be generally categorised as: bare (eliminating all residue interference), mulch (allowing some soil disturbance) and no-till (no soil disturbance). A field may have multiple management units types present either spatially (e.g., strip tillage), or temporarily (e.g., no-till fallow/planting, followed by inter-row cultivation). Ridge till systems allow crop residues and seeds shattered on the soil surface to be moved to the inter-row zones, thus creating a bare ridge unit and a mulch furrow unit (Forcella and Lindstrom, 1988).

Table 1
General applicability of non-chemical weed management tactics in three types of management units within tillage systems

Category	Weed management tactic	Management unit type		
		Bare	Mulch	No till
Cultural	Crop rotation, competitive cultivars	+	+	+
	Crop row spacing, planting density	+	+	+
	Adapt planting time to weed emergence	+	+	+
	Fertilizer rate and placement	+	+	+
	Compost	+	+	±
	Reduce weed seed import (machines, seed, manure)	+	+	+
Tillage	Stubble cultivation	+	+	−
	Ploughing	+	−	−
	(Repeated) seedbed preparation	+	±	−
Mulches	Cover crops, dead mulch	±	+	+
	Green mulch, intercrops	+	+	±
	Solarisation/plastic mulch	+	±	±
	Artificially applied mulch	+	+	+
Thermal	Flaming	+	±	±
	Hot water/air	+	+	+
	Band steaming	+	±	−
Mechanical	Interrow cultivation	+	+	+
	Rotary hoeing	+	+	±
	Hoeing close to the crop row	+	−	−
	Weed harrowing	+	−	−
	Intra-row weeders	+	±	−
	Inter-row mowing/slashing	+	±	+
	Weed seed collection	+	+	+
Biological	Mycoherbicides	+	+	+
	Resident herbivores and plant or seed pathogens	−	±	+
	Maintaining permanent seed predator habitats	−	±	+

+: Good possibilities, ±: serious restrictions, −: not applicable. Experimental technologies (e.g., laser cutting, water jet cutting, UV radiation, electroporation) are excluded.

2.2. No-till management units

Although the no-till type seems best suited to expose weed seeds at the soil surface and sustain predator populations (Brust and House, 1988; Harrison et al., 2003), Cardina et al. (1996) and Cromar et al. (1999) did not find different predation rates in mouldboard-ploughed and no-till crop fields. Mice, beetles and birds may consume large amounts of weed seeds, but the amounts vary with species, time and space (Lutman et al., 2002; Harrison et al., 2003; Westerman et al., 2003). The contribution of seed predators to reducing weed numbers is largely unknown, and depends on whether weed numbers are seed-limited (species with low fecundity and non-persistent seedbanks) or limited by the availability of safe sites (species producing many long-lived seeds)(Forcella, 2003; Harrison et al., 2003). Tillage practices greatly affect safe site availability for both weed seeds and predators.

Few curative non-chemical methods are applicable on no-till units. Pre-emergence thermal weeding using hot water (Kurfess and Kleisinger, 1999; Hansson and Ascard, 2002), steam (Kolberg and Wiles, 2002) or recycling hot air (Bertram, 1996) prevent fire hazards in dry residues but are relatively costly. Hot water applied to narrow strips (20% of the field area) with small weeds would require approximately 1.6 m^3 water ha^{-1} and 20 kg propane ha^{-1} (derived from Hansson and Ascard, 2002). Combining strip flaming and punch planting (Rasmussen, 2003) allows for crop establishment without soil disturbance, which reduces and delays weed germination. Although corn, onions, sunflower and cabbages tolerate postemergence flaming (Casini et al., 1994; Netland et al., 1994; Peruzzi et al., 1998), the potential for selective thermal weed control is yet restricted and requires further research (Bertram, 2002).

Weed growth can be smothered by competitive crops, residues, green mulch or cover crops. They are predominantly managed by herbicides (Gallagher et al., 2003; Teasdale and Rosecrance, 2003) to prevent crop yield loss and compensate for inconsistent and short-lived weed suppression (Yenish et al., 1996; Teasdale and Abdul-Baki, 1998). Sowing cover crops or cash crops immediately after harvest may effectively suppress weeds (Vallejos et al., 2001 in Derpsch, 2002), and with appropriate mechanisation to selectively harvest crops and flexibly tune planting time, intercropping may be a viable alternative (Baumann et al., 2000). Mowing, slashing, undercutting or rolling may control inter-row weeds and manage cover crops and intercrops (Kuepper, 2001; Creamer and Dabney, 2002). Residues may also be moved into crop rows to suppress weeds (Cramer, 1991).

2.3. Mulch and bare management units

Mulch units use non-inverting tillage to retain crop residues on the soil surface. They offer additional options such as using false seedbeds, post-planting rotary hoeing and inter-row cultivation, and post-harvest cultivations to kill weeds, manage intercrops and dilute weed seeds. Although current high-residue cultivators cause little residue incorporation and fragmentation, frequent cultivations may compromise the aims of conservation tillage.

Bare management units are created by full-field ploughing to damage and expose perennial weeds, and bury weeds, seeds and residues. This facilitates the use of false seedbeds (Caldwell and Mohler, 2001; Rasmussen, 2004), flaming, band steaming (Melander et al., 2002) and mechanical weeding. Bare units provide the widest range of non-chemical tactics (Table 1), but tillage and the absence of residues might adversely affect weed management, by destroying seed predator habitats, decreasing topsoil workability and stability, and enhancing weed emergence. Mechanical weeding in current mouldboard plough systems is compromised by uneven soil surfaces and reduced trafficability.

2.4. Spatial arrangements and precision

Wide sprayer booms and cultivation equipment generally provide indiscriminate treatment of crop rows, inter-row spaces and rows of standing residue. Real-time kinematic differential global positioning systems (RTK-DGPS) automatic guidance has recently enabled accurate and permanent delineation of management units, as narrow as individual crop rows. Precision guidance could enhance integrated weed management by:

(1) Appling weed management treatments preferentially to row and inter-row zones. This makes methods indicated for bare units applicable to conservation tillage systems. For example, when row positions of subsequent crops are shifted sideward precisely, shallow hoeing between rows of standing stubble and growing crops might avoid residue disturbance in no-till fields.
(2) Tuning multicrop row spacing and planting times to optimise canopy height and width development over time may improve weed suppression and ease management by strip mowing, selective harvesting or lateral soil movement. Thus, adjacent management units may compensate lack of weed manageability or soil protection. For example, intra-row weeders may frequently cultivate narrow strips, without compromising soil protection by inter-row residues or cover crops.
(3) Planned movement of management zones over time could allow flexible crop planting and diversified multi-year tillage sequences (e.g., sowing the next crop before harvesting the standing crop). These could be geared to crop and weed lifecycles (Section 4.2), overcoming the fixed sequence and timeliness restrictions of most mechanised systems and allowing overlap in crop and tillage cycles.
(4) Spatial diversification to manipulate resource availability and capture to the disadvantage of weeds (Liebman and Gallandt, 1997). Different rotations (of crops and tactics) on distinct strips could be combined to exploit small-scale spatio-temporal interactions between crops, weeds, pathogens and beneficial organisms. The concept of dedicating zones to specific functions is not new (Larson, 1964) and provided the key to make mulch systems work (Kuepper, 2001) and alleviate problems such as seedbed warming (Swan et al., 1996) and traffic-induced compaction (Chamen et al., 1994), but mechanisation is the key problem in translating scientific knowledge into practicable crop, field and soil designs (e.g., Section 4.3).

The applicability of non-chemical weed management tactics seems not determined by the type of tillage system *per se*, but primarily by how they are designed and managed. The following sections indicate how management system designs can be matched to the requirements of specific weed management tactics (i.e., mechanical weeding) and to the exploitation of natural processes and weaknesses in the weed's lifecycles (i.e., enhanced weed seed mortality).

3. Mechanical weeding

3.1. General possibilities and limitations

Mechanical weeding is an essential component of most organic cropping systems, as there are few alternatives to control intra-row weeds after crop emergence (Table 1). Rotary hoes and weed harrows control intra-row and inter-row weed seedlings in a wide range of crops at a high work rate (up to 15 ha h^{-1}). When these implements or band spraying are combined with inter-row cultivation, they can efficiently cut down herbicide use by 50–70% (Van der Weide et al., 1993; Forcella, 2000). The shallow cutting action of steerage hoes and inter-row cultivators may kill over 90% of the inter-row weeds (Estler et al., 1992; Pullen and Cowell, 1997). Stirring the cut layer by weed harrowing or powered rotors improves weed control to over 95% and controls large weeds as well, even in moist weather conditions (Weber, 1997; Lenski et al., 2002).

Intra-row strips can simultaneously be cultivated by torsion weeders, finger weeders, brush weeders (Ascard and Bellinder, 1996; Bowman, 1997; Melander, 1997), pressurised air (Lütkemeyer, 2000) or other tools. As these tools utilise differences in susceptibility to mechanical damage between weeds and the crop, only young weeds can be controlled after crops are sufficiently robust to withstand the tool's uprooting and soil covering action. Limited applicability and effectiveness of this approach in susceptible, slowly growing, shallowly planted crops (e.g., sugar beet, onions and carrots), causes major weed management problems in organic agriculture, and high labour requirements for manual weeding (50–300 h ha^{-1}) (Gianessi and Sankula, 2003). The low and unreliable intra-row weeding effectiveness found with current tillage systems and machinery (generally 25–70%; Estler et al., 1992; Bleeker et al., 2002) appears largely due to untimely control of the largest weeds (Kurstjens et al., 2002b; Fig. 1) and does not adequately reflect the potential of mechanical weeding (Kurstjens et al., 2002a).

3.2. Improving mechanical weeding

Intra-row mechanical weeding would be facilitated by (Kurstjens et al., 2002a):

(1) Highly accurate automatic depth control and steering, allowing an increased proportion of area to be treated, and rapid, precise implement adjustment. Weeding tools are generally spring-mounted or attached to parallelograms carried by wheels running between crop rows, so that even small irregularities in elevation or soil strength induce working depth deviations. Adjusting tools can be cumbersome, resulting in inferior performance (Kurstjens and Bleeker, 2003).
(2) Fine, level seedbed strips that remain friable under a wide range of conditions until canopy closure, allowing for a gentle implement action in sensitive crops, tool penetration to shallow depths (10–20 mm) without residue interference, improved capability of weed burial or root exposure and desiccation.
(3) Improved trafficability, allowing more timely treatment when weeds are small and weather and topsoil conditions favourable. In temperate moist climates, lack of trafficability narrows the time window available for cultivation (Hanna et al., 2000), raises farmer concerns on soil structure deterioration and may impede timely weeding (Wicks et al., 1995; Kempenaar et al., 2004). This requires smaller wheel loads and inflation pressures, and greater implement width and soil strength.

Current tillage systems and machinery rarely meet these requirements, but controlled traffic with high-precision zone tillage can fulfil all three. Controlled traffic would help maintain level fields and improve implement stability, allowing for more precise tool control and simplified depth adjustment. Controlled traffic employing light tractors (e.g., 1500 kg, 20 kW) to pull wide (e.g., 12–18 m) cultivators tilling narrow (e.g., 8 cm wide near crop) strips would minimise soil disturbance and fuel consumption and extend the workable period considerably (Kempenaar et al., 2004). Wide high-speed (up to 16.9 km h^{-1}; Hanna et al., 2000) auto-steer cultivators could revolutionise weed management by providing a low-cost alternative to spraying, allowing many timely intra-row cultivation passes. Inter-row weeds and cover crops could be mowed or cultivated less frequently. Once frequent, precise and timely cultivations are technically feasible, strategies to adapt cultivation timing and mode of action (covering, uprooting) to weather conditions could be developed, to minimize costs and risks of weed control failure during spells of wet weather.

3.3. Precise cultivation

Melander and Hartvig (1997) and Northway and Tullberg (2000) showed that the untilled strip width could be reduced to about 50 mm without inducing crop damage. Vision guidance may allow for a knife spacing of 60 mm at speeds up to 11 km h^{-1} (Home et al., 2001), whereas guidance by buried markers has been claimed to achieve 5-mm accuracy (R. Tucker, personal communication, 2004).

Precision is also the key to enhance the performance of intra-row tools. In laboratory weed harrowing trials on sandy soil, plants were rarely uprooted if tine-plant spacing exceeded 10 mm and working depth did not exceed sowing depth by more than 5–10 mm (Kurstjens et al., 2000). Tines create small-scale heterogeneous patterns of uprooting and covering damage (Kurstjens et al., 2000; Kurstjens and Perdok, 2000), which might be utilised in tuning the mode of action to crop and weed susceptibility and improving selectivity in early crop growth stages (Kurstjens and Bleeker, 2003). Preliminary laboratory trials with millimetre-precise steering and depth control indicated that sugar beets could be harrowed at the emergence and 2-leaf stage, without significant plant losses (Eroglu and Kurstjens, unpublished data) whereas excessive crop damage (Wevers, 1995; Ascard and Bellinder, 1996) currently restricts weed harrowing until after the 4–6-leaf stage. This is a problem because weed susceptibility declines rapidly after they emerge (Peters et al., 1959; Gunsolus, 1990; Rasmussen, 1996; Fig. 1).

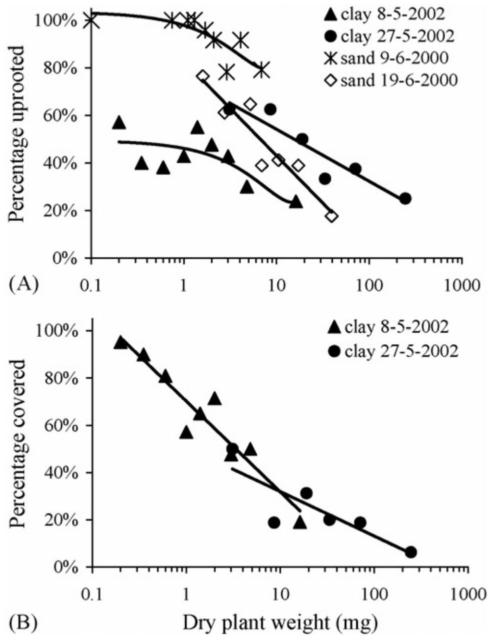

Fig. 1. The percentage of *Poa annua* L. plants uprooted (A) or covered (B) by torsion weeding as related to individual plant dry weight at cultivation. Data on two subsequent intra-row cultivations on sand and clay soil from Kurstjens (2002) reflect within-population variation of weed susceptibility and the impact of different tool adjustment and soil conditions.

3.4. Topsoil conditions

Differences in weed uprooting due to varying topsoil properties are important (Fig. 1). Topsoil conditions affect soil disturbance patterns (as related to covering; Fogelberg and Kritz, 1999; Kurstjens and Perdok, 2000), uprooting (Kurstjens et al., 2000) and plant anchorage forces (Fogelberg and Dock Gustavsson, 1998; Kurstjens et al., 2004). Interactions between these parameters are imperfectly understood (Rasmussen, 1996; Kurstjens et al., 2002b), but friable seedbeds generally facilitate a shallow, non-aggressive tool adjustment and favour exposure and desiccation of uprooted weeds (Mohler, 1996; Mohler et al., 1997; Bleeker et al., 2002). No-till systems, cover crops and living mulches increase topsoil organic matter and improve tilth (Hartwig and Ammon, 2002), and so might assist mechanical weeding. Precise residue placement between the rows could overcome blockage problems with shanks entering into the soil at the edges of the residue-free crop strips. Banding, chopping and incorporating (inter)crop residues into narrow strips (e.g., 80 mm wide) might eventually create an extremely workable, stable topsoil for fast, uniform crop establishment and improved intra-row weeding.

Kurstjens (2002) explored whether adapted seedbeds could improve selectivity of uprooting weeds and decrease crop susceptibility to mechanical weeding. A sugar beet planter equipped with sprayer nozzles created crusted strips on either side of the crop row, while providing a 3-mm strip of non-crusted soil immediately above the seed row and stronger soil immediately beneath (Fig. 2A). The split-crust impeded weed emergence without impeding crop establishment, and anchored emerged weeds in the topsoil. Intra-row torsion weeding broke the crust on the weak line above the crop seed, moving the crust and weeds anchored in it away from the row (Fig. 2B and C). This one-season experiment could not be seen as conclusive, but it does illustrate how seedbeds might be usefully re-engineered.

4. Enhancing weed seed mortality

4.1. Weed ecology and tillage functions

Improvements to the functionality of tillage weed management tactics might also be considered from an ecological perspective. Several papers have reviewed the ecological principles of non-chemical weed management (e.g., Mohler, 1996; Liebman and Gallandt, 1997), and stressed that knowledge of weed biology and ecology is essential to develop, optimise and integrate weed

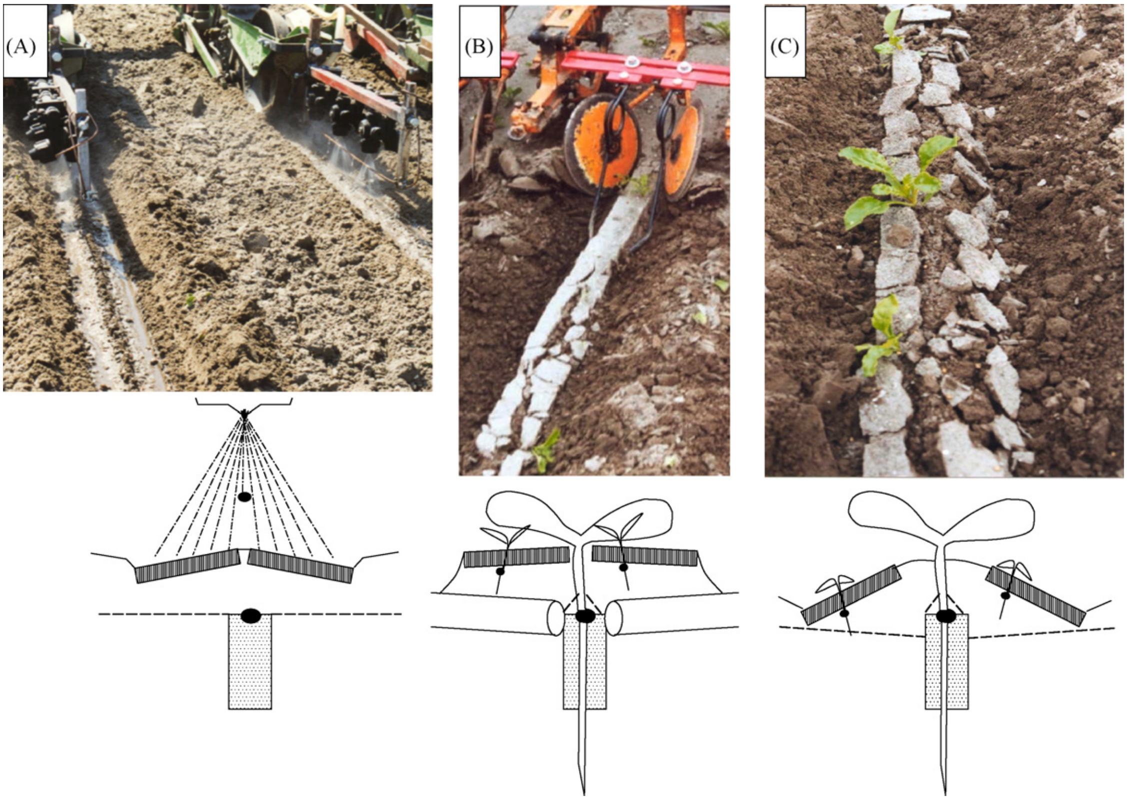

Fig. 2. Pictures (top) and corresponding schematic seedbed cross-sections (bottom) of a sugar beet seeder adapted with nozzles, creating an artificial crust with a weak spot above the seed (A), torsion weeders breaking the crust in two parts, falling into the trenches created by disks on either side of the row (B), and the result achieved with adequate working depth and steering (C) (Kurstjens, 2002).

management tactics. Reliance on measures such as mechanical weeding can be reduced if the number of weeds emerging in unfavourable locations (within the row) and periods (shortly before and after crop establishment) could be reduced. This might be achieved by:

(1) Collecting and removing weed seeds mechanically (Kahrs, 1998; Matthews et al., 2004) or reducing the production and viability of weed seeds by mulches and competitive crops that pre-empt resources, have allelopathic effects or alter the physical environment (Liebman and Gallandt, 1997).
(2) Improving weed seed exposure to predators while sustaining seed predator populations (Cromar et al., 1999; Harrison et al., 2003).
(3) Enhance fatal germination, pre-emptying the soil seedbank in periods and locations that allow for relatively easy weed control (Forcella, 2003; Hartmann et al., 2003; Rasmussen, 2004).
(4) Extending the period of seed burial at depths from which they cannot emerge. Although clear relationships between seed longevity and soil properties have not been found (Albrecht and Auerswald, 2003; Bekker et al., 2003), burial depth, soil moisture and organic amendments affect seed decay (Fennimore and Jackson, 2003; Forcella, 2003).
(5) Preventing weed emergence or shifting the time of emergence relative to the crop, to give the crop a competitive advantage, provide additional opportunities for weed control, and increase intra-row weeding selectivity (Bullied et al., 2003; Rasmussen, 2003).
(6) Damaging plants (e.g., by mechanical weeding, slashing, predation or other biological agents) and disrupting belowground storage organs of perennial weeds.

Although tillage can employ all these principles, they are only effective in certain stages within the weed and cropping cycle (Fig. 3). Inadequate implementation and sequencing often restrict their effectiveness.

4.2. Functional tillage sequencing

Most current mechanised systems do not allow cropping and tillage cycles to overlap, as all treatments

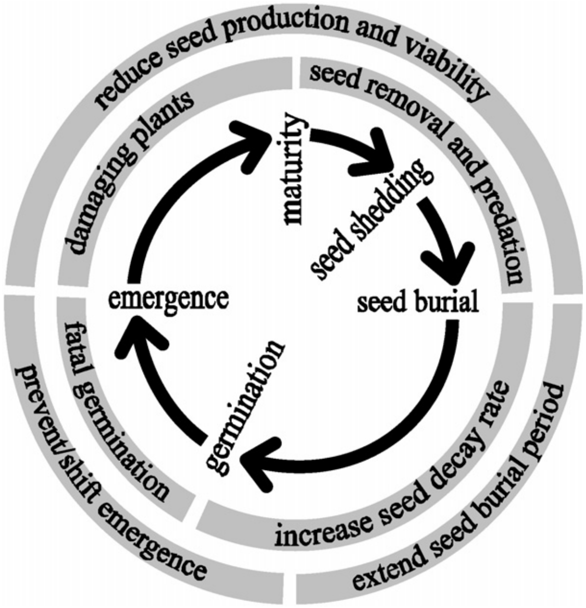

Fig. 3. The applicability of the six weed management principles outlined in Section 4.1 as related to the lifecycle of seed-propagated weeds.

must be carried out full-field in a fixed sequence within relatively short periods. For example, post-harvest stubble cultivation kills remaining weeds (principle 6) and induces germination of newly shattered seeds (principle 3), but impedes seed predation (principle 2) by making seeds inaccessible to predators and potentially disturbing their habitat. Although the goal is to prevent seedbank replenishment by stimulating germination of freshly shattered seeds, this tactic may increase weed seedling densities in next year's crop (Anderson, 1999; Melander and Rasmussen, 2000). Ideally, tillage should fully exploit principle 2 (e.g., in summer and autumn) and 3 (e.g., in spring and summer) first, before incorporating the remaining seeds into the seedbank (Harrison et al., 2003), particularly if seed decay rates are low as compared to the duration of the burial period.

However, extending the controlled traffic approach with precise strip treatments could improve flexibility in matching management to weed and crop lifecycles, and allow application of a greater range of the principles noted in Section 4.1. For example, a biennial cultivation system that exhausts the topsoil seedbank by 2–3 inter-row cultivations in a competitive spring barley crop, reduced weed emergence in next year's crop (planted in the same strip without ploughing) by 52–77%, as compared annual ploughing (Melander, 1999).

4.3. Improving soil and residue manipulations

Annual mouldboard ploughing effectively buries weed seeds for 1 year, but in the subsequent 5 years, approximately 75% of those seeds will be repositioned in the top layer, from which they can emerge (based on simulations using the seed displacement matrix derived from the model of Roger-Estrade et al., 2001). Other ways to transpose soil, residues and weed seeds might extend the seed burial period (by avoiding mixing of seeds produced in different years through the same soil volume), minimise soil disturbance and maintain residue cover on the surface.

For example, a multi-year high-precision strip tillage system could dispose surface soil, residue and seeds in narrow vertical slots and put ‘‘clean’’ excavated soil back onto the cropped strip, while maintaining surface residues between crop rows (Fig. 4). If further seed

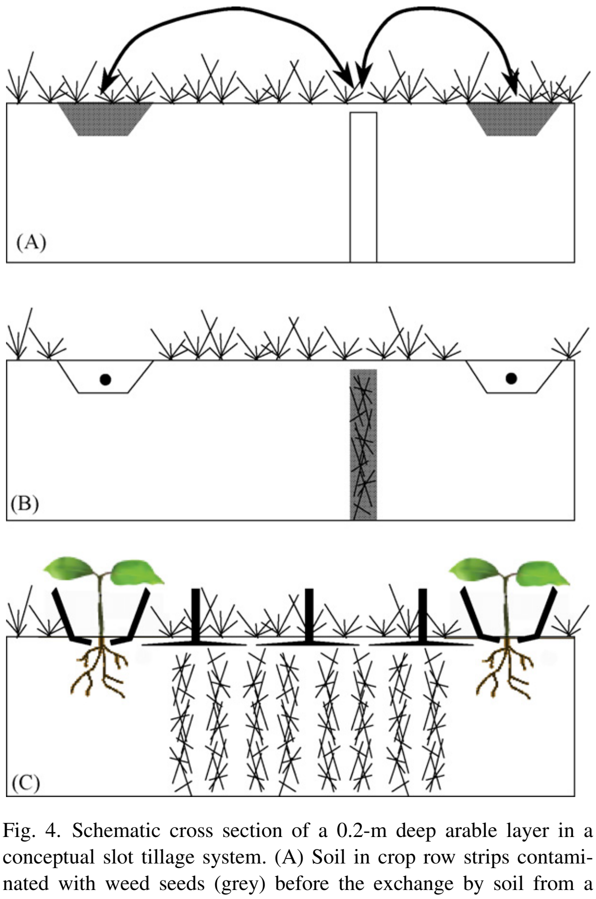

Fig. 4. Schematic cross section of a 0.2-m deep arable layer in a conceptual slot tillage system. (A) Soil in crop row strips contaminated with weed seeds (grey) before the exchange by soil from a narrow strip containing few weed seeds (white). (B) After exchanging soil, crop is sown in strips containing only few seeds. (C) Situation after 7 years with laterally shifted slots in which residue and weed seeds can decay. Surface residues between crop rows are maintained or cultivated, preventing new weed seeds from entering into the slots, whereas residue-free crop strips can be weeded mechanically.

incorporation into the slots is prevented and if slots are shifted laterally in subsequent years, it may take many years before the same soil is re-excavated to serve as a seedbed. For example, soil from two 8-cm wide 5-cm deep strips could be exchanged with soil from one 4-cm wide 20 cm deep slot. With sufficient precision and 75 cm row spacing, 6 cm slot spacing would theoretically allow seeds to decay for 15 years. This would considerably reduce seed survival as compared to annual ploughing (Fig. 5).

Annual ploughing effectively depletes transient seedbanks, but most arable weed species have more persistent seed banks (Burnside et al., 1996; Thompson et al., 1997). As the surviving seeds were produced under a known herbicide and fertilisation regime, combining shifted slot tillage with proper crop and herbicide rotation could offer great opportunities for delaying herbicide resistance. It may also increase the uniformity and predictability of weed emergence flushes.

There may be other ways to implement principle 4 and preventing seeds mixing, without compromising the other principles and objectives of conservation tillage. If combined with controlled traffic, combining 16 row strips into one 32-cm wide ‘slot’ could make the idea more technically feasible and applicable on heavy, stony or self-mulching soils. Rotations including root crops and vegetables requiring ridges or soil-disturbing harvesting methods might require other adaptations, such as deeper burial or occasional banded application of weed-free compost in crop strips. Unconventional ways to implement other principles should be considered as well.

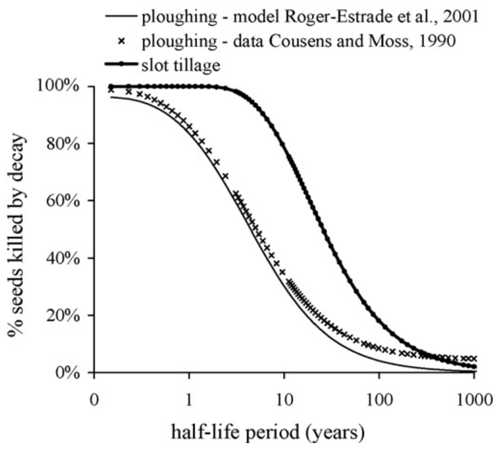

Fig. 5. Simulated relationship between weed seed longevity and the percentage of seeds lost by decay in soil for annual ploughing and a slot tillage system (Fig. 4), assuming exponential seed decay, 50% germination of seeds moved to the top 0.05-m layer, and a slot re-excavation period of 15 years. Seed displacement by ploughing was simulated by a four-layer matrix based on data from Cousens and Moss (1990) and from a model including the effect of a skim coulter (Roger-Estrade et al., 2001).

5. Challenges for tillage research

Effective herbicides have allowed tillage system development to focus on other issues than weed management. Diversifying rotations and implementing a wider range of non-chemical tactics based on ecological principles are required to reduce herbicide reliance and sustain conservation tillage (Derksen et al., 2002). Shifting to more integrated approaches requires knowledge of complex ecosystem behaviour, new tactics, and methods to combine multiple tactics in a space-specific way (Liebman and Gallandt, 1997; Buhler et al., 2000; Buhler, 2002). This may be supported by on-farm research, guidelines, decision aids (Pannell, 2000; Rasmussen et al., 2002) and cycles of monitoring, diagnosis, design, pre-evaluation and implementation (Altieri and Liebman, 1988).

However, low product prices force farmers to drastically reduce labour and machinery costs (Orson et al., 2003), so they would rather simplify weed management than adopt complex knowledge-intensive systems that require additional investments and adaptations. Therefore, developing tillage systems that can flexibly and easily employ a wide diversity of tactics without compromising other farm objectives (e.g., complexity, risks, costs, management efforts, soil conservation) is pivotal to the success of integrated weed management and truly sustainable conservation tillage.

First, this implies that the weed management function of all crop/soil operations (e.g., sowing, harvesting) should be maximised, to minimise the need for additional operations (e.g., mechanical weeding, spraying). Second, additional operations should be cheap, versatile and avoid outcomes that restrict the effectiveness and applicability of other operations. Improving non-chemical backup control measures could help farmers to accept risks imposed by weather conditions or lack of experience (Kuepper, 2001). Supplementary tactic(s) should target weak spots in the weed management toolbox (e.g., with respect to selection pressure, cost-effectiveness, reliability) first, to maximise the marginal value of adaptations.

The examples in this paper indicate that controlled traffic and high-precision strip tillage facilitate the integration of mechanical and thermal weeding, enhanced weed seed mortality and soil and residue conservation. This would require tools that accurately manipulate small strips without affecting the adjacent area (Chamen, 2000) rather than implements treating large widths randomly and homogeneously. Function-oriented redesign to exploit spatially diversified soil/crop patterns could improve system coherence and eliminate many of the compromises inherent within designs that evolved in the herbicide era. This might start with a more thorough analysis of the requirements of non-chemical weed management, and exploration of new ways to implement weed management principles.

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