This volume of the *Topics in Canadian Weed Science* series is the result of a one day symposium that was held during the 2007 Annual Meeting of the Canadian Weed Science Society - Société canadienne de malherbologie in Mont-Tremblant, Québec, on November 27th 2007.

Weed science is a comprehensive discipline that encompasses a broad array of domains, from plant biology and population dynamics to crop management and weed control methods. Weed control methods are generally grouped under the following general labels: preventive, biological, cultural, physical and chemical. Physical weed control represents but one of these broad categories and is the object of this volume. The physical weed control techniques presented in this volume involve mostly tillage and thermal weed control.

It is hoped that the reader, after having read the contents of this volume, will be more aware of the progress and innovations that have taken place in physical weed control science and that they will shed the common perception that these control methods are old-fashioned and outdated. Although this volume deals mostly with physical weed control methods, the reader should also keep in mind that this is but one weed control method and that it should be considered as one of the tools within a weed management toolbox available to producers. In some circumstances, it might be the only tool available or usable but it could also complement other weed control methods and should not be excluded from consideration.

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Physical weed control: Progress and challenges

Topics in Canadian Weed Science Volume 6

Physical weed control:
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Edited by
Daniel C. Cloutier and Maryse L. Leblanc

Canadian Weed Science Society
Société canadienne de malherbologie

Topics in Canadian Weed Science **Volume 6**

Physical weed control: Progress and challenges

Edited by

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Preface

The Canadian Weed Science Society – Société canadienne de malherbologie (CWSS-SCM) is pleased to present the sixth volume of *Topics in Canadian Weed Science.* This volume is a compilation of peer-reviewed papers that were presented at the plenary session of the 2007 CWSS-SCM annual meeting held in Mont Tremblant, Quebec. The theme of the plenary session arose from the CWSS-SCM Physical Weed Control Working Group, who felt there was a need to disseminate information on this alternative form of weed control to the general membership, producers and the public. This volume is unique in that it is a comprehensive account of physical weed control research in both North America and Europe.

Topics in Canadian Weed Science is intended to advance the knowledge of weed science and increase awareness of the economic and environmental impact of weeds in agro-ecosystems, forestry, and natural habitats. The volumes cover a wide range of topics and provide a diverse source of weed science information.

The plenary session topics at the CWSS-SCM annual meeting are of both national and global interest, and we invite weed science professionals from around the world to attend our annual meetings. The annual meeting is held in mid- to late November, with locations alternating between Eastern and Western Canada. Information on the CWSS-SCM annual meeting is available on the website (www.weedscience.ca/home).

The CWSS-SCM Board of Directors expresses their gratitude to Daniel Cloutier and Maryse Leblanc for editing this volume; the Mont Tremblant Local Arrangements Committee, the contributing authors, and the reviewers who made this publication possible. Other volumes in this series include:

Volume 1: *Field boundary habitats: implications for weed, insect, and disease management*
Volume 2: *Weed management in transition*
Volume 3: *Soil residual herbicides: science and management*
Volume 4: *Invasive plants: Inventories, strategies, and action*
Volume 5: *The first decade of herbicide-resistant crops in Canada*
Volume 7: *The politics of weeds*

These volumes are available for purchase and can be ordered through the CWSS-SCM website.

Eric Johnson
Publications Director, CWSS-SCM

Acknowledgements

Cover

Top photograph: Cultivation of corn using a rotary hoe.

Middle photograph: Cultivation of pickling cucumber using the Buddingh finger weeder.

Bottom photograph: A cereal field being cultivated with a Hatzenbichler spring tine.

Cover Design for the Series: Ralph Underwood, Agriculture and Agri-\Food Canada, Saskatoon Research Centre, Saskatoon, SK.

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La lutte physique : Progrès et défis

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Introduction

This 6th volume of the Topics in Canadian Weed Science series is the result of a one day symposium that was held during the 2007 Annual Meeting of the Canadian Weed Science Society - Société canadienne de malherbologie in Mont-Tremblant, Québec, on November 27th 2007. The symposium consisted of 9 oral presentations and was complemented by 14 related posters on physical weed control.

Weed science is a comprehensive discipline that encompasses a broad array of domains, from plant biology and population dynamics to crop management and weed control methods. Weed control methods are generally grouped under the following general labels: preventive, biological, cultural, physical and chemical. Physical weed control represents but one of these broad categories and is the object of this volume.

Physical weed control is a lot more than just mechanical weed control with a row crop cultivator although this is probably the image that first springs to mind to the uninitiated. The chapter by van der Weide et al. does show that physical weed control methods have never stopped improving and that they truly belong to the modern cropping managements systems and to the future.

According to the Physical and Cultural Weed Control working group of the European Weed Research Society, physical weed control includes the following techniques: mechanical weed control, soil tillage, thermal weed control, mulching, solarization and electromagnetic weed control (http://www.ewrs.org/pwc/working_group.asp).

The physical weed control techniques presented in this volume involve mostly tillage and thermal weed control. According to the American Society of Agricultural and Biological Engineers (ASABE), in agriculture, tillage generally refers to the changing of soil conditions for the enhancement of crop production (ASABE, 2009a, b). They further distinguish between primary, secondary and cultivating tillage.

Primary tillage is the first major soil working operation and its purpose is to reduce soil strength, to cover plant materials, and to rearrange aggregates (ASABE, 2009b). Although primary tillage is carried out yearly as part of the regular field operations in cropping systems relying on soil inversion, it is generally taken for granted by most weed researchers and professionals but is rarely considered from a weed management point of view. Peruzzi et al. wrote a chapter titled "Primary tillage" where they review the various categories of implements used for primary tillage and their effect on weed control.

Secondary tillage usually refers to tillage operations following primary tillage and commonly done at a more shallow depth than the primary tillage operation. The purpose of these secondary tillage operations is to prepare the seedbed while incorporating soil amendments, fertilizers, and pesticides. These operations also level and firm the soil, and control weeds (ASABE, 2009b). Peruzzi et al. present the various types of implements used for secondary tillage and their weed control implications in the chapter titled "Secondary tillage".

Cultivating tillage used to be referred to as "tertiary tillage" in older terminology documents produced by the ASABE. It refers to implements that perform shallow post-plant tillage to loosen the soil and/or to control weeds. Examples of cultivating tillage implements are: row crop cultivators, rotary hoes, spring tine harrows and rotary tillers, among others. Leblanc and Cloutier present mechanical weed control in cereal crops in Eastern Canada while Johnson et al. present mechanical weed control in pulse and cereal crops in Western Canada. Boyd and Van Acker follow with a chapter on the impact of tillage on weed populations and on the soil environment.

Another category of physical weed control methods, thermal weed control, is presented in the chapter by Ascard and van der Weide. A group of weed scientists from the Netherlands, Sweden and Denmark are presenting the current state of physical weed control in North-Western Europe while discussing the challenges that they face in the future in the chapter by van der Weide et al. The current state of precision agriculture is presented by Panneton along with some of the challenges ahead.

We certainly hope that the reader, after having read the content of this volume, will be more aware of the progress and innovations that have taken place in physical weed control science and that they will shed the common perception that these control methods are old-fashioned and outdated.

Although this volume deals mostly with physical weed control methods, the reader should also keep in mind that this is but one weed control method and that it should be considered as one of the tools within a weed management toolbox available to producers. In some circumstance, it might be the only tool available or usable but it could also complement other weed control methods and should not be excluded from consideration.

The editors wish to thank the authors and the reviewers for their contribution to this volume of the Topics in Canadian Weed Science series.

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ASABE. 2009b. Terminology and definitions for agricultural tillage implements. *ASAE Standards: ASAE S414.2 MAR2009*, 13 pp.

Primary tillage

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Introduction

According to the American Society of Agricultural and Biological Engineers (ASABE, 2009a), tillage refers to the mechanical manipulation of soil for the enhancement of crop production. In cropping systems based upon soil inversion, primary tillage is the first major soil working operation and its purpose is to reduce soil strength, to cover plant materials, and to rearrange aggregates (ASABE, 2009b).

It is an aggressive operation which is usually carried out at a considerable depth. It generally leaves an uneven soil surface and it does provide some control of annual weed species by burying some of their seeds at depths that prevents them from emerging (Kouwenhoven, 2000). However, primary tillage can also partially control perennial weeds by burying some of their propagules, thereby preventing or slowing down their emergence. Also, primary tillage can bring up some seeds or vegetative propagules to the soil surface. Once on the surface, these propagules will be exposed more directly to the weather and to desiccation conditions (Cloutier and Leblanc, 2001; Mohler, 2001). The primary tillage tools that are regularly used are mainly: mouldboard ploughs, disc ploughs, powered rotary ploughs, diggers, and chisel ploughs (Barthelemy et al., 1987; Peruzzi and Sartori, 1997; Cloutier and Leblanc, 2001; ASABE, 2009a).

Mouldboard ploughs

Actually, mouldboard ploughs are surely the most widely used tools to perform primary tillage in soil inversion cropping systems. Mouldboard ploughs may be simple, reversible and polyvalent (Figure 1). The first ones are equipped only with right mouldboards. Thus they turn the soil only on the right, while the reversible (equipped with both right and left mouldboards) and polyvalent (equipped with cylindrical outlined "blade mouldboards" that can be inclined on the right and the left with respect to the driving direction) ploughs are able to turn the soil both on the right and on the left, thus reducing working times, fuel consumption and costs of the operation (Barthelemy et al., 1987; Peruzzi and Sartori, 1997).

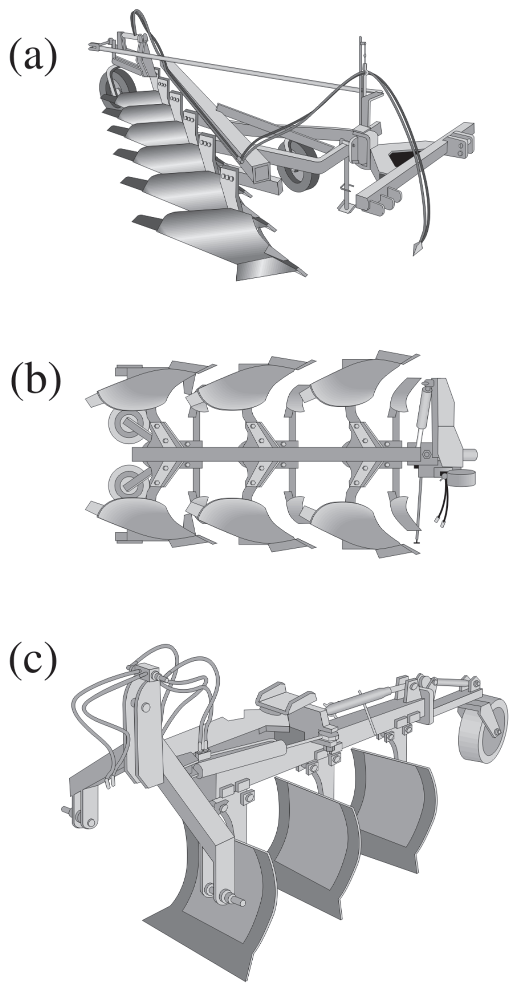

Figure 1. Simple (a), reversible (b) and polyvalent (c) ploughs (Peruzzi and Sartori, 1997).

The ploughs are mainly characterized by the shapes of the mouldboard. In this respect, the ploughs may be equipped with "conventional" mouldboards (cylindrical, helicoidal and "universal" – partly cylindrical and partly helicoidal) (Figure 2). More innovative mouldboards, lozenge and strips shaped (Figure 3), decrease drawbar pull (10-30 %) with respect to conventional mouldboards and perform ploughing properly in wet and plastic heavy soils. Moreover, lozenge mouldboards are able to enlarge the furrows allowing the tractor to work "in furrow", reducing soil compaction caused by tires (Figure 4). Mouldboard ploughs are the best when it comes to soil overturning (optimal value is close to 135° in order to maximize soil roughness and gas incorporation in the soil) (Figure 5), allowing control of both actual and potential weed flora. In order to increase the degree of control of the vegetative and reproductive structures of perennial weeds and/or to reduce the risks of further weed development after primary tillage, the mouldboard ploughs can be equipped with jointers that bury a portion (placed on the left if the soil is turned on the right) of the turned clods, thereby reducing the emergence and development of the weeds where it is more "dangerous" (the contact area between adjacent clods) (Figure 6). The shape and type of the jointers should be adjusted according to weed density, biomass and aggressiveness (Figure 7) (Barthelemy et al., 1987; Peruzzi and Sartori, 1997).

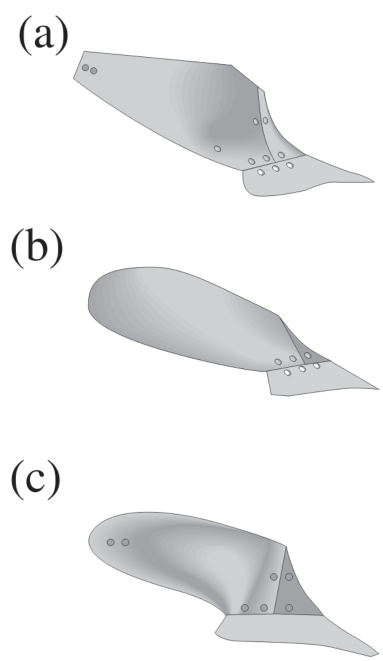

Figure 2. Conventional mouldboards: (a) cylindrical, (b) helicoidal, (c) universal (Peruzzi and Sartori, 1997).

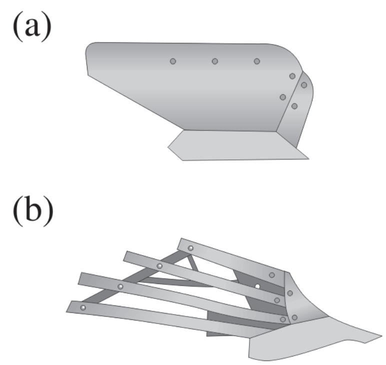

Figure 3. Innovative mouldboards: (a) lozenge, (b) strips shaped (Peruzzi and Sartori, 1997).

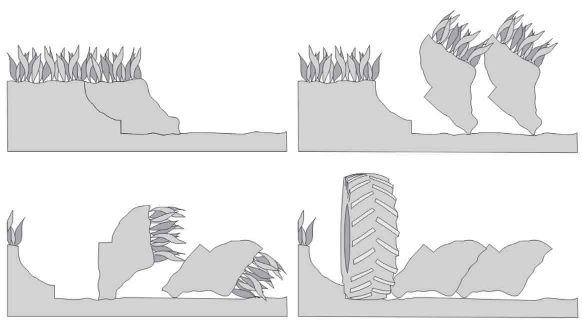

Figure 4. Schematic diagram of action of lozenge mouldboard plough with tractor working “in furrow” (Peruzzi and Sartori, 1997).

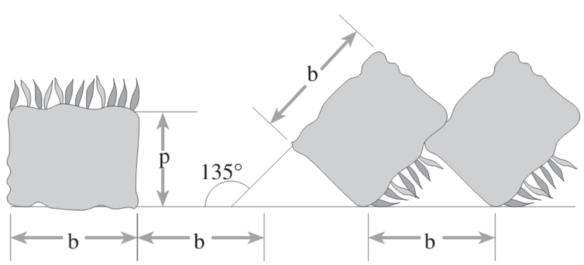

Figure 5. Schematic diagram of theoretical plough soil overturning: p= working depth; b=working width; b= p1/2 (Peruzzi and Sartori, 1997).

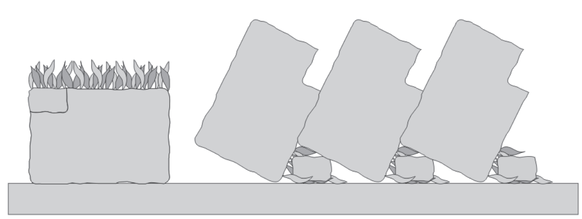

Figure 6. Schematic diagram of action of jointer during mouldboard ploughing (Peruzzi and Sartori, 1997).

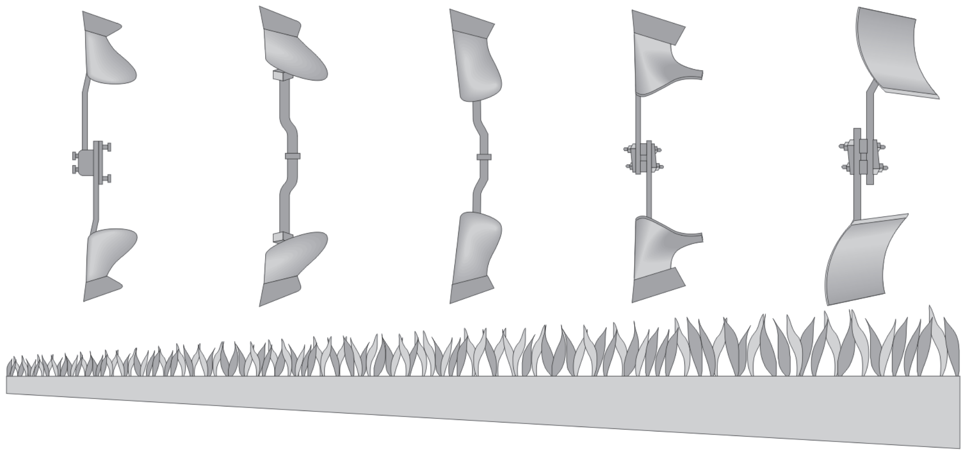

Figure 7. Jointers of different typology suited to work properly with increasing weed presence and biomass (Peruzzi and Sartori, 1997).

The working depth of mouldboard ploughs can vary from 15-20 cm (shallow ploughing) up to 30-50 cm (deep ploughing). Deep ploughing is more effective in controlling actual and potential weed flora, including propagules of perennial species (Kouwenhoven, 2000), but it is responsible for a high degree of oxidation of the organic matter and it increases working time, energy use and costs. Shallow ploughing is economical, "conservative" and it is able to control actual and potential weeds including perennial species if the plough units are equipped with proper jointers (Barthelemy et al., 1987; Peruzzi and Sartori, 1997).

However, one of the main disadvantages of mouldboard ploughing is the formation of an significant and heavy sole at the end of the furrow, where the share cuts the soil horizontally. This can cause problems both for the proper vertical movement of water in the soil profile and for the development of the crop root system. This disadvantage can be more critical when shallow ploughing is performed but it is possible to prevent this problem by equipping the plough with rigid tines that act as sub-soilers (Figure 8). Sub-soil ploughing can replace both deep and shallow ploughing and achieve the same level of weed control while avoiding their disadvantages (Figure 9) (Barthelemy et al., 1987; Peruzzi and Sartori, 1997).

When ploughing is used as the only technique to perform primary tillage in cropping systems based upon soil inversion, it is better to often vary the working depth in order to avoid the homogenous distribution of weed seeds in the tilled layer. This can be particularly problematic when the seed-bank is large. Effectively, although soil inversion will bury actual and potential weed flora, it can also bring up a lot of viable weed seeds if the seed-bank is substantial, thereby nullifying the weeding effect of ploughing. Consequently, ploughing should be performed at different depths, taking into account the needs of the crops included in the cropping system and/or sometimes substituting other primary tillage techniques that do not cause soil inversion such as chiselling, sub-soiling, harrowing, etc. (Bàrberi et al., 1998, Mohler, 2001; Bàrberi, 2002).

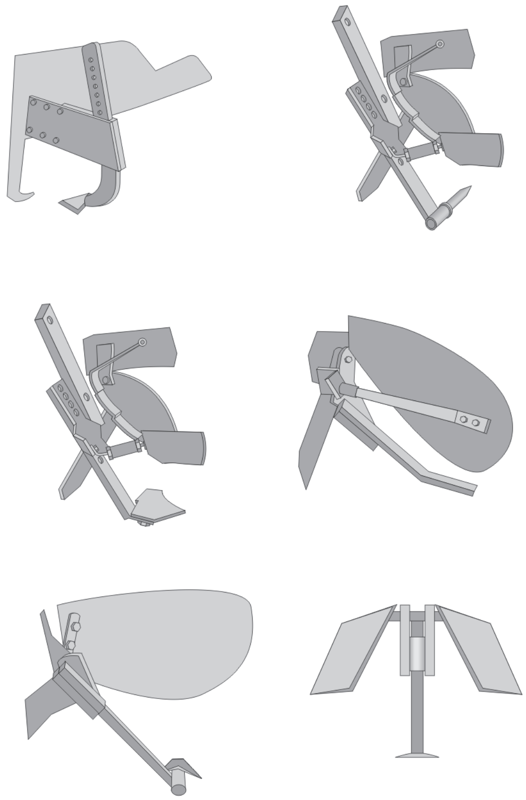

Figure 8. Mouldboard ploughs equipped with different typology of subsoiler tines (Peruzzi and Sartori, 1997).

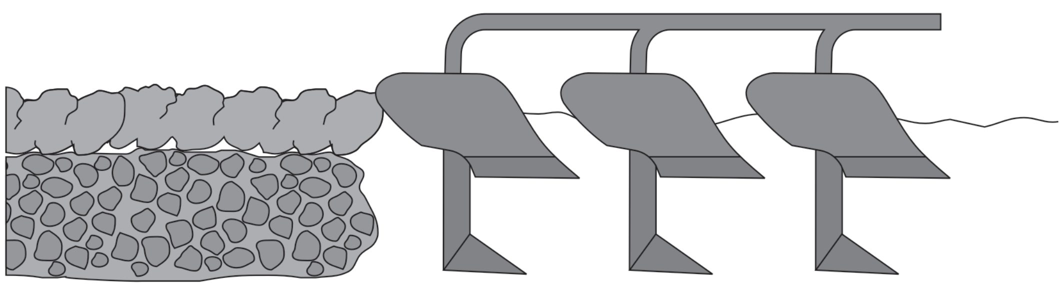

Figure 9. Schematic diagram of action of mouldboard subsoil-ploughing (Peruzzi and Sartori, 1997).

Disc Ploughs

Disc ploughs are divided in “standard” and “vertical” tools. In standard disc ploughs, several idle discs are mounted on axial and parallel pins, inclined with respect to both the soil surface and driving direction (Figure 10). Vertical disc ploughs are characterized by a large number of units. In this case, the discs are flanged on the same horizontal axle, that is parallel to soil surface, and inclined with respect to driving direction (Figure 11). Disc ploughing decreases drawbar pull, working times, fuel consumption and costs in comparison with mouldboard ploughing because the sliding friction between the soil and the discs is partly transformed in rolling friction (Figure 12). Similar to the mouldboard ploughs, disc ploughs can also be equipped with jointers and sub-soilers (Figure 13). Disc ploughing causes a high crumbling and an important stirring of the tilled soils. However, it is less effective than the mouldboard plough in turning the soil and does not control weeds as well, especially perennial weed species. For this reason, the use of disc ploughs is limited, particularly in cropping systems based on soil inversion where only physical weed control is performed (ASABE, 2009b; Barthelemy et al., 1987; Peruzzi and Sartori, 1997).

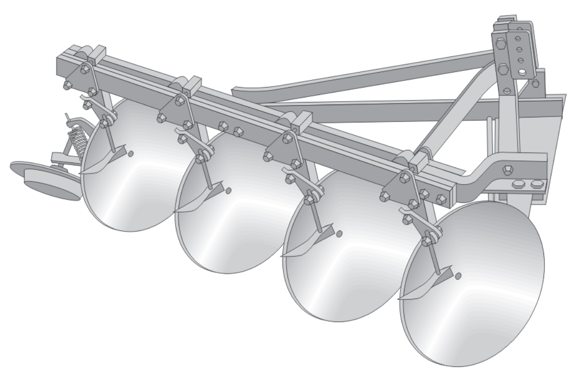

Figure 10. Standard disc plough (Peruzzi and Sartori, 1997).

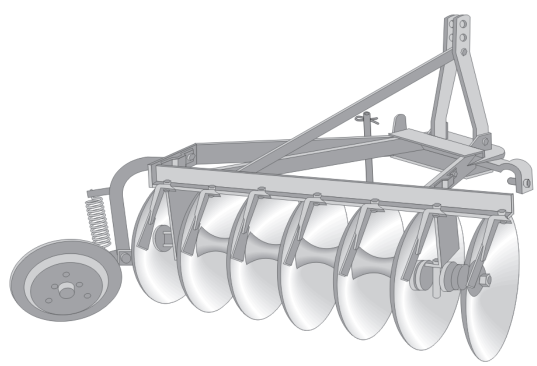

Figure 11. Vertical disc plough (Peruzzi and Sartori, 1997).

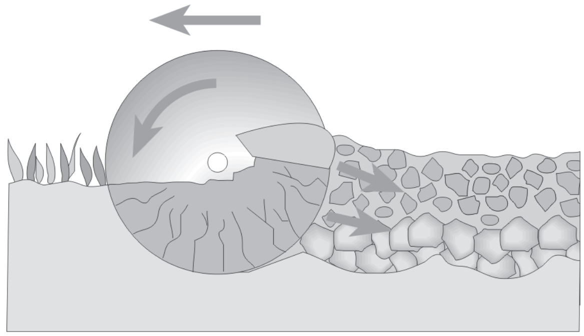

Figure 12. Action of disc plough (Peruzzi and Sartori, 1997).

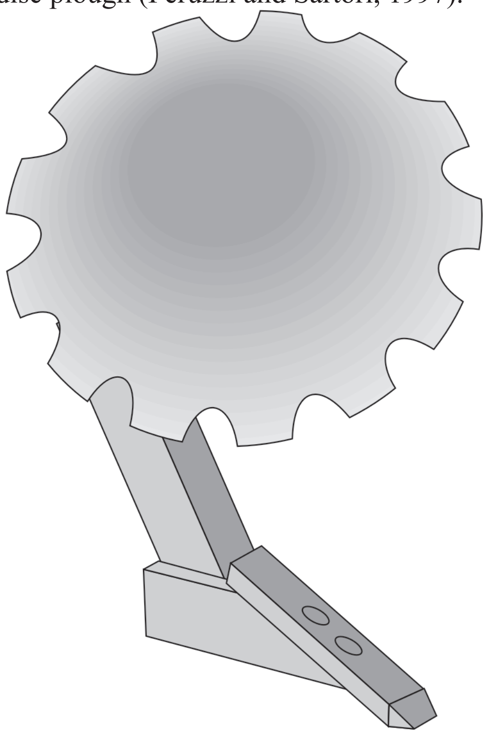

Figure 13. Disc subsoil-plough (Peruzzi and Sartori, 1997).

Rotary ploughs

Rotary ploughs are rear-mounted implements characterized by a horizontal rotor inclined approximately 60° with respect to driving direction and powered by the tractor power take-off (PTO) (Figure 14). The working tools flanged on the rotor may be blades (able to properly work in dry heavy soils) (Figure 15) or discs (able to properly work in wet soils) (Figure 16) and their number may vary from 5-7 (disc rotor) to 6-12 (blade rotor). The rotor works at a low speed, ranging from 90 to

150 rpm and performs a “strip” tillage of the soil, causing most of the clods to crumble and partially overturning the soil to a depth of 25-35 cm (Figure 17). The rotary plough is very effective in utilizing the tractor power as it greatly reduces drawbar pull while it strips the soil without the risk of forming a plough sole. Like the disc plough, the rotary plough is not effective in controlling weeds. Consequently this tool should be used with caution in cropping systems based on soil inversion where only physical weed control is performed (ASABE, 2009b; Barthelemy et al., 1987; Peruzzi and Sartori, 1997).

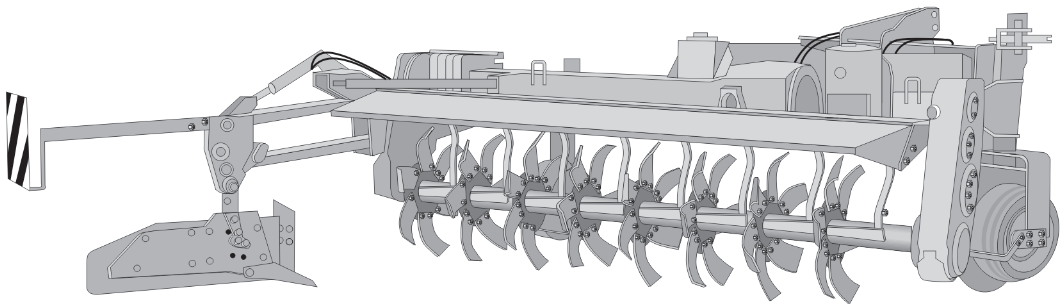

Figure 14. PTO powered rotary plough (Peruzzi and Sartori, 1997).

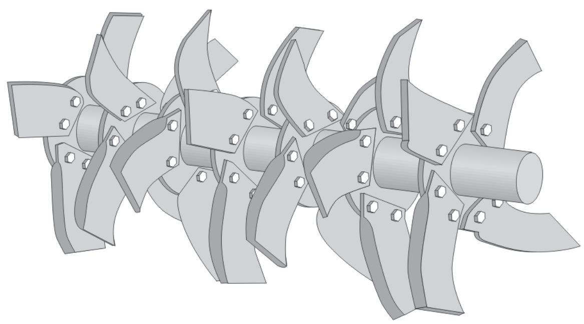

Figure 15. Rotor of PTO powered rotary plough equipped with blade tools (Peruzzi and Sartori, 1997).

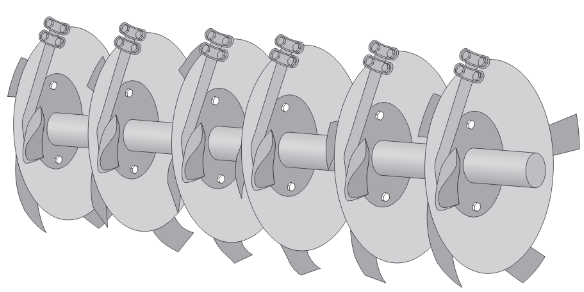

Figure 16. Rotor of PTO powered rotary plough equipped with disc tools (Peruzzi and Sartori, 1997).

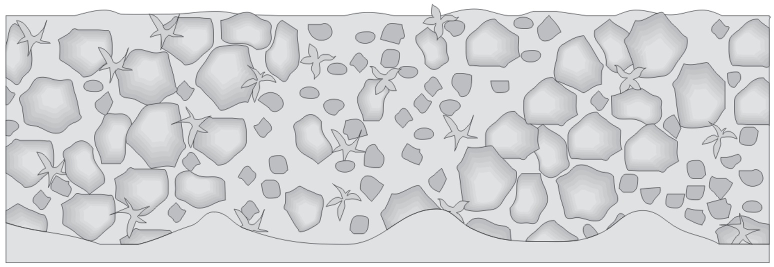

Figure 17. Section of soil tilled by PTO powered rotary plough (Peruzzi and Sartori, 1997).

Diggers

Diggers are mounted implements powered by the tractor PTO and equipped with spades having a trapezoidal shape (Figure 18) that are placed on the final part of the connecting rod of an articulated parallelogram (Figure 19). The handles create a spade motion that cuts a 15-20 cm wide soil slice, crumble the soil, and throws it in the direction opposite to the tractor movement (Figure 20). Diggers driving speed is usually low (1-2 km h^{-1}), but it may be higher (up to 3-4 km h^{-1}) when more recent and advanced implements are used with very high (up to 400 rpm) rotating speed of the spades. The use of the diggers is associated with a high degree of soil crumbling, which may be made more or less intensive by adjusting the position of the rear clod shield (Figure 21). There is no risk of tillage sole forming, reduced soil compaction and an optimized use of tractor power since no drawbar pull is needed. Moreover, the diggers may be also equipped with sub-soiler tools (Figure 22). On the other hand, the diggers produce an incomplete soil turning compared with the mouldboard ploughs; thus their weeding action is effective only on actual flora while it is not effective on potential flora. Using the diggers may actually increase infestations with perennial weeds since the vegetative and reproductive structures are cut and not buried in the soil, thus potentially propagating them. Consequently, diggers must be used with caution in farming systems where weed management is performed without herbicides, especially in the presence of a perennial weed species infestation. When diggers are used to perform primary tillage, the physical weed control strategy will have to rely on the effects of the subsequent tillage interventions (secondary tillage, seed-bed preparation, false seed-bed technique, etc.) (ASABE, 2009b; Barthelemy et al., 1987; Peruzzi and Sartori, 1997).

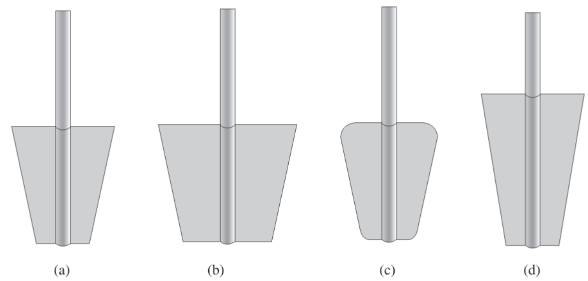

Figure 18. Spades used as tools in the diggers: (a) conventional; (b) large; (c) rounded; (d) elongated (Peruzzi and Sartori, 1997).

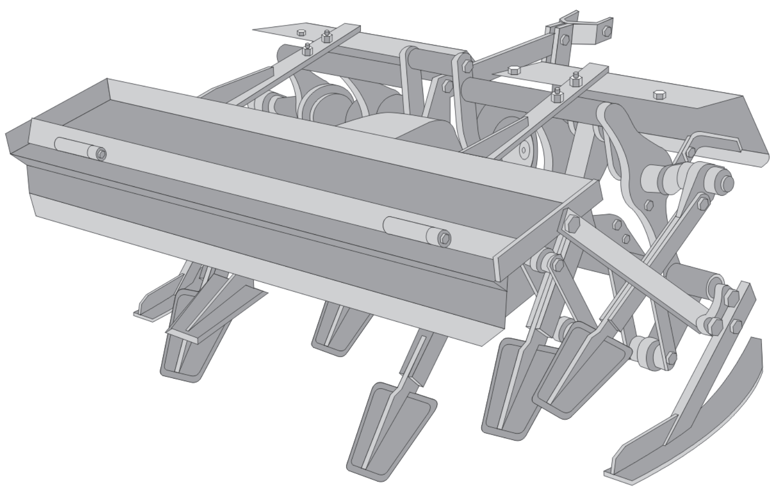

Figure 19. Schematic diagram of a digger (Peruzzi and Sartori, 1997).

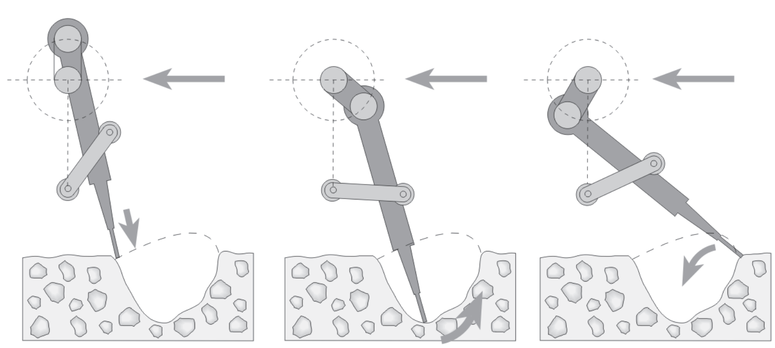

Figure 20. Schematic diagram of the action of a digger (Peruzzi and Sartori, 1997).

Chisel ploughs

The chisel ploughs are not real ploughs as they are ineffective in performing soil inversion. They are considered as soil conservation tools. These implements vary greatly among models and makes but they are always equipped with rigid tines, placed on a straight or “V” shaped frame, inclined with respect to soil surface and to which a variety of points, shovels or sweeps can be attached (Figure 23). The working depth may vary from 25-30 cm to 50-60 cm. The action of the chisel plough results in a soil that is crumbled and lifted to the surface as it slides off the edges of the tines, breaking into large diameter clods, similar to those produced by ploughing (Figure 24). Chiselling requires less working time, less fuel and costs than moldboard ploughing at the same depth. Moreover, this technique helps in conserving the soil organic matter content and in removing the plough sole when present in soils that are regularly mouldboard ploughed (Barthelemy et al., 1987; Peruzzi and Sartori, 1997).

The weeding action of the chisel ploughs is effective only on the actual flora while the potential flora is not controlled because there is no soil inversion. However, chisel ploughing may help control perennial weeds as a portion of their vegetative and reproductive structures are brought to the soil surface where they can be destroyed by being exposed directly to the weather conditions. Since chisel ploughing does not control the potential flora, the strategy for physical weed control should rely on the effects of the other tillage interventions such as secondary tillage, seed-bed preparation, false seed-bed technique, etc. However, in cropping systems based on mouldboard ploughing, the use of chisel ploughs at least every third or fourth year may improve soil conditions and structure while removing the plough sole. It may also increase weed infestation levels, consequently greater attention has to be paid to the subsequent tillage operations (Bàrberi, 2002; Barthelemy et al., 1987; Mohler, 2001; Peruzzi and Sartori, 1997).

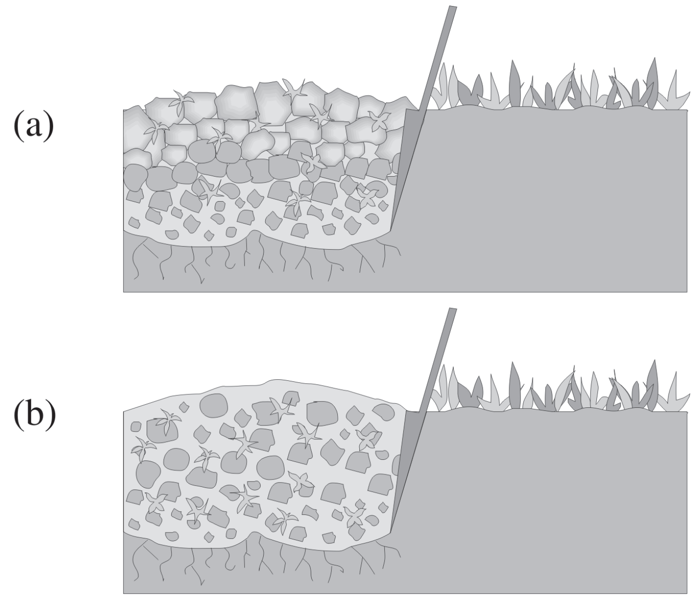

Figure 21. Section of soil tilled by a digger with open (a) and closed (b) rear clod shield (Peruzzi and Sartori, 1997).

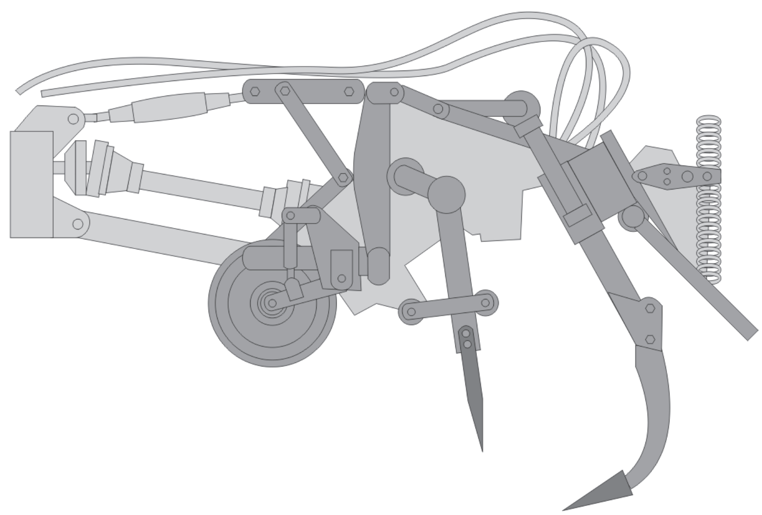

Figure 22. Digger equipped with a rear subsoiler (Peruzzi and Sartori, 1997).

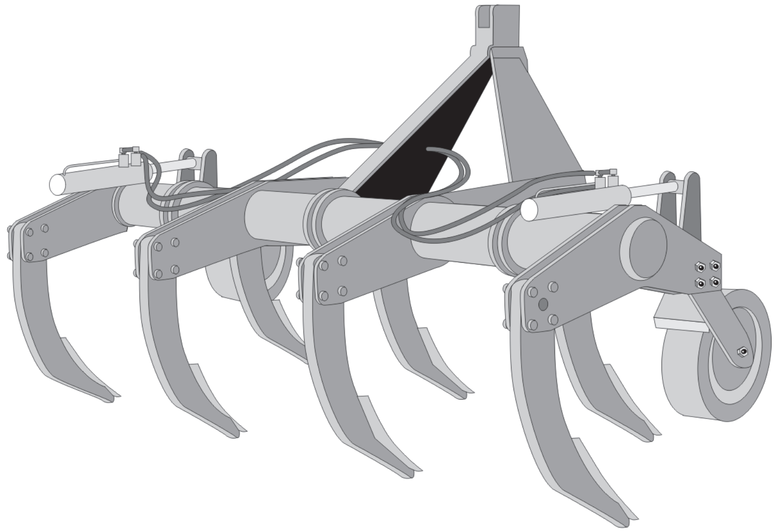

Figure 23. Chisel plough equipped with a “V” shaped frame (Peruzzi and Sartori, 1997).

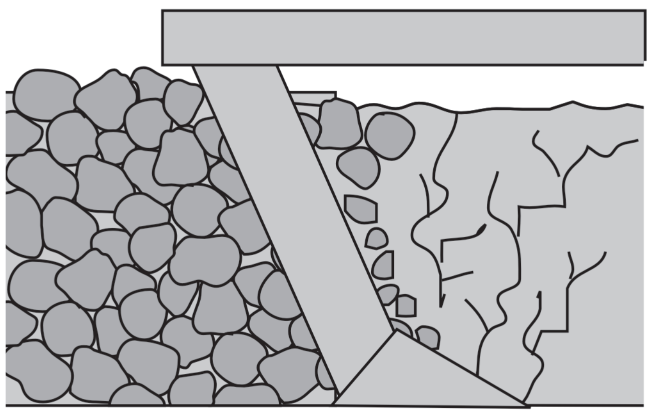

Figure 24. Schematic diagram of chisel ploughing (Peruzzi and Sartori, 1997).

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Secondary tillage

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Introduction

Tillage refers to the mechanical manipulation of soil for the enhancement of crop production, according to the American Society of Agricultural and Biological Engineers (ASABE, 2009a). Secondary tillage usually refers to a group of different tillage operations following primary tillage and commonly done at a shallower depth than the primary tillage operation. The purpose of these secondary tillage operations is to prepare the seedbed while incorporating soil amendments, fertilizers, and pesticides. These operations also level and firm the soil, and control weeds (ASABE, 2009b). Secondary tillage implements are various types of cultivators, harrows, and PTO powered machines. Under some field conditions, secondary tillage implements could be used to prepare fields instead of the common primary tillage equipments (Barthelemy et al., 1987; Peruzzi and Sartori, 1997). Some typical secondary tillage implements are presented below.

Cultivators

Cultivators (Figure 1) can be equipped with rigid or flexible tines 45-60 cm high, spaced 15-30 cm, and working to a depth of 15-25 cm on ploughed soil. The frame consists of 2-4 beams and may be mounted or drawn. The higher the number of beams, the smaller the risk of the tool being plugged by crop and weed residues. The tines may be rigid or flexible. The rigid tines are often partly or completely curved (Figure 2) and are used for more aggressive operations. The flexible tines are usually curved (Figure 3) and are used for milder operations.

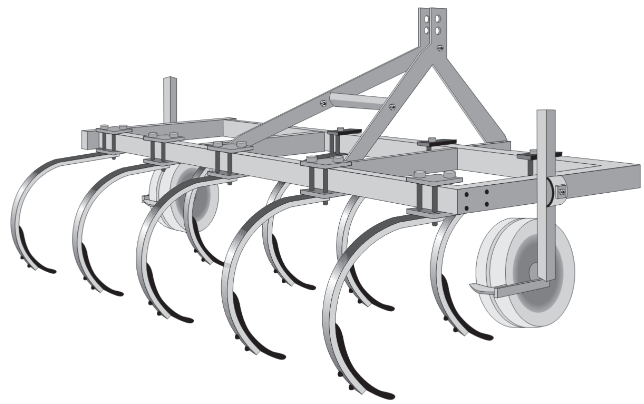


Figure 1. Cultivator equipped with rigid tines (Peruzzi and Sartori, 1997).

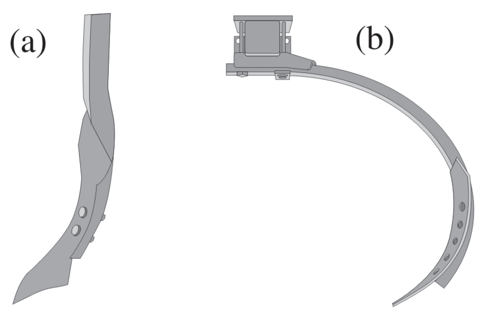


Figure 2. Rigid tools mounted on cultivators: (a) straight tine, (b) curved tine (Peruzzi and Sartori, 1997).

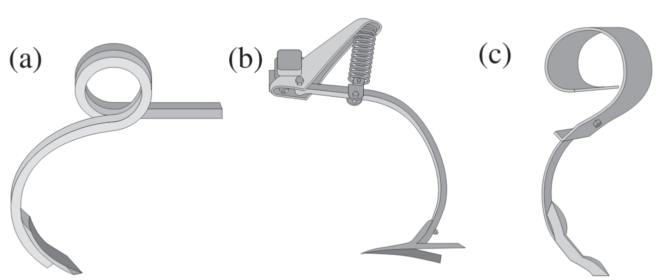


Figure 3. Flexible tools mounted on cultivators: (a) double spring tine, (b) spring-curved tine (c) spring-flat narrow tine (Peruzzi and Sartori, 1997).

The tip of the tines can be equipped with teeth of different shapes: wide tools such as the goose foot will provide better weed control while narrow tools which usually work at a greater depth will crumble and stir the soil, reducing clod size (Figure 4). The use of the cultivators does control weeds but it might also increase weed germination and emergence (Bàrberi, 2002; Barthelemy et al., 1987; Mohler, 2001; Peruzzi and Sartori, 1997).

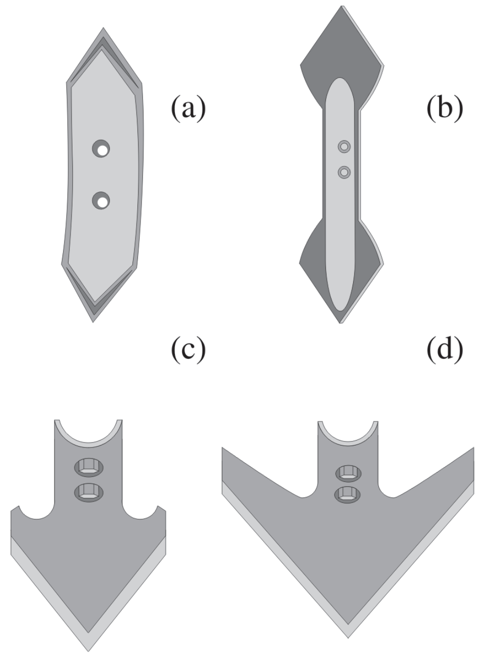


Figure 4. Devices mounted on flexible tools of cultivators: (a) conventional narrow devices, (b) rounded narrow device (c) goose foot devices (d) wide goose foot device (Peruzzi and Sartori, 1997).

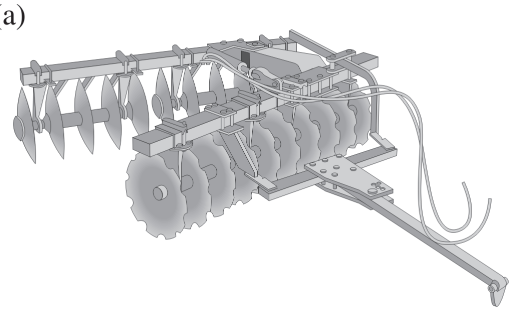
Harrows

Harrows are implements equipped with different type of tools (discs, flexible and/or rigid tines, radial blades, etc.) that further crumble, stir, and loosen the soil before planting. The different tools have different effects on the soil and different weeding actions. For this reason, several implements are modular and can be equipped with a combination of tools of diverse shapes in order to perform different actions on the soil and on the weeds in a single passage. Combined harrows can also be used to directly prepare the seedbed in a single passage both in tilled and untilled soils (ASABE, 2009b; Barthelemy et al., 1987; Mohler, 2001; Peruzzi and Sartori, 1997).

Disc harrows

There are several different types of disc harrows. The offset disc harrow is equipped with two opposite disc gangs, working one behind the other. The tandem disc harrow is a X-shaped disc harrow with two opposed front gangs and two opposed rear gangs (Figure 5) (Buckingham, 1984). Discs are concave, circular, and can have an edge that is either smooth or notched (Figure 6). Working depth ranges between 10 and 20 cm. Soil crumbling and stirring can be increased by changing the angle between the axles, up to a maximum value of 40-50°. The notched discs are usually placed in the front to increase the efficacy of the harrow on clods or untilled soil while smooth discs are placed in the rear. Disc harrows can be effective in crumbling and stirring the soil, in controlling actual weed flora and in burying weed and crop residues. Unfortunately, they may stimulate weed seed germination and may cause the forming of an important sole that may negatively affect crop growth and development (Figure 7). Therefore, they must be used with caution, especially in wet, plastic soils, or, preferably, combined with rigid tines able to break the sole (ASABE, 2009b; Barthelemy et al., 1987; Peruzzi and Sartori, 1997).

(a)



(b)

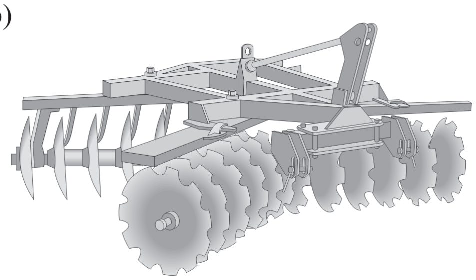


Figure 5. Schematic diagram of disc harrows: (a) off-set; (b) tandem (Peruzzi and Sartori, 1997).

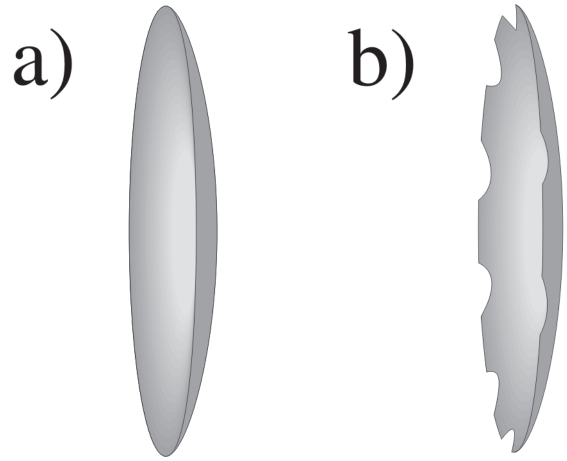


Figure 6. Disc mounted on disc harrows: (a) smoothed disc; (b) notched disc (Peruzzi and Sartori, 1997).

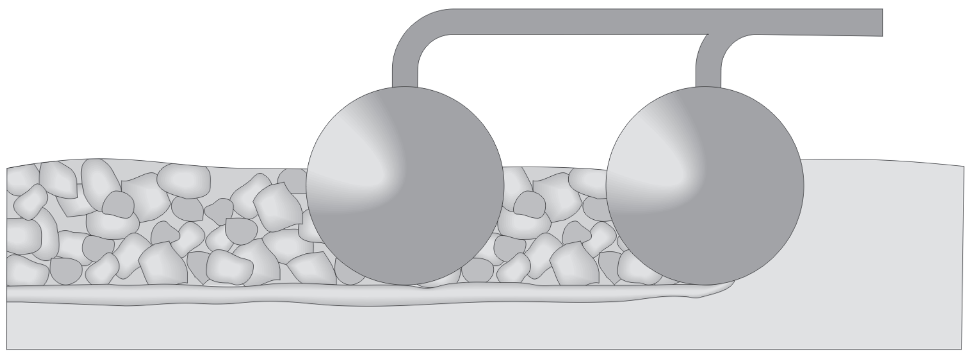


Figure 7. Schematic diagram of a superficial and heavy sole formed by disc harrows (Peruzzi and Sartori, 1997).

Spring tine harrows

Spring tine harrows are often made up of modular frames 25-35 cm high (with respect to the soil surface) on which the flexible tines are staggered and mounted on a number of rows (Figure 8). This leaves sufficient space between the tines to prevent plugging by crop or weed residues. In these implements, the form and the flexibility of the tines makes them vibrate when the tractor moves, crumbling the soil and controlling weeds that are present. This activity might also stimulate the emergence of more weeds. The working depth can vary from 5-6 cm to 10-12 cm, with the latter depth being more aggressive. The type and shape of the tines will also affect how aggressive the implement will be. For example, the implement will be more aggressive if simple or double curved tines are used (Figure 9) and less aggressive if reversible curved tines, narrow flexible tines or Canadian tines are used (Figure 10). These harrows are often used in combination with a packer or roller harrow and/or disc or blade harrows to improve soil crumbling, weed control and soil surface levelling before planting (ASABE, 2009b; Barthelemy et al., 1987; Peruzzi and Sartori, 1997).

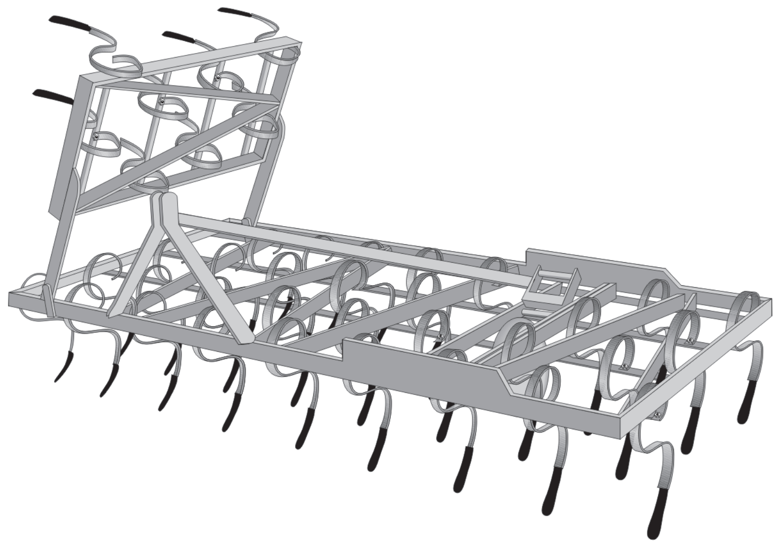


Figure 8. Schematic diagram of spring tine harrow (Peruzzi and Sartori, 1997).

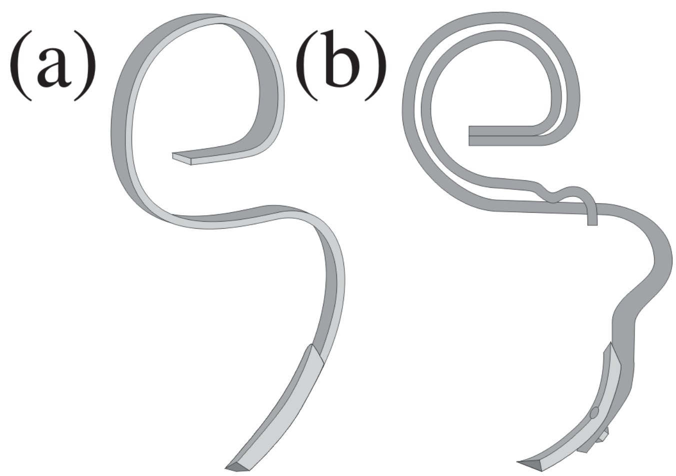


Figure 9. Schematic diagram of single (a) and double (b) curvature tines mounted on spring tine harrows (Peruzzi and Sartori, 1997).

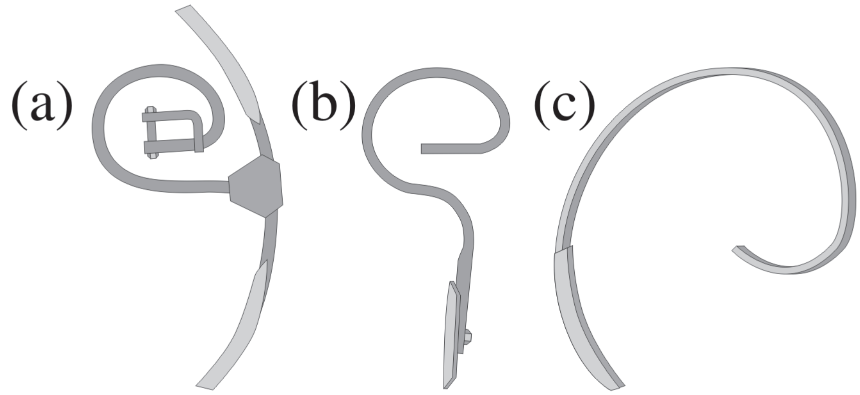


Figure 10. Schematic diagram of reversible curved (a), narrow flexible (b) and Canadian (c) tines mounted on spring tine harrows (Peruzzi and Sartori, 1997).

Rigid tine harrows

Rigid tine harrows are modular and work superficially in the field, crumbling and levelling the soil. In fact, the frame works as a levelling blade because the tines only reach a depth of a few centimetres (Figure 11). Consequently, these harrows are totally ineffective in controlling weeds since they would quickly become plugged in the presence of any plant residue (ASABE, 2009b; Barthelemy et al., 1987; Peruzzi and Sartori, 1997).

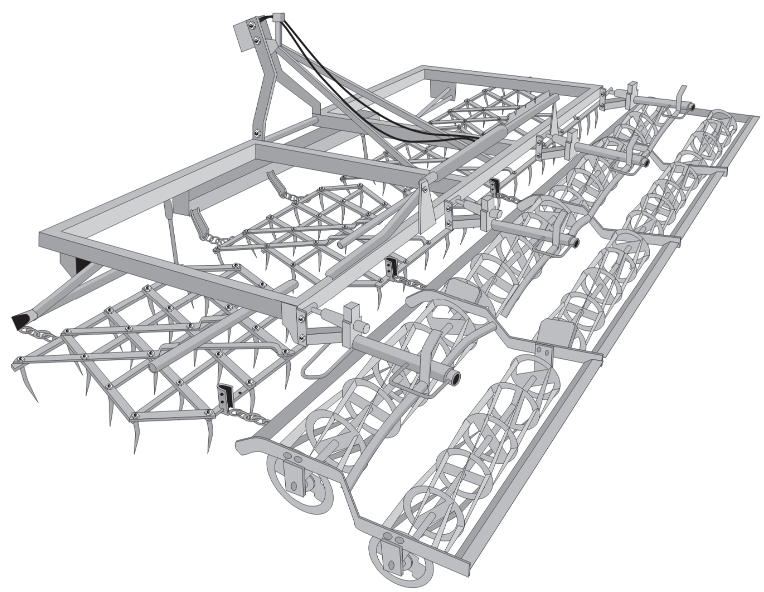


Figure 11. Schematic diagram of modular rigid tine harrow (Peruzzi and Sartori, 1997).

Radial blade harrows

Radial blade harrows have 2-4 axles placed on a frame rear-mounted to the tractor. They are equipped with a series of cross shaped blades inclined with respect to the rotation axle. The axles are in turn inclined with respect to the driving direction (Figure 12). These harrows work very superficially, loosening the soil to a depth of 3-5 cm. They are particularly well suited to preparing seed-beds in wet, heavy soils. These harrows have a good weeding action on weeds already emerged but they can also stimulate the emergence of weed seeds present in the topsoil layer (ASABE, 2009b; Barthelemy et al., 1987; Peruzzi and Sartori, 1997).

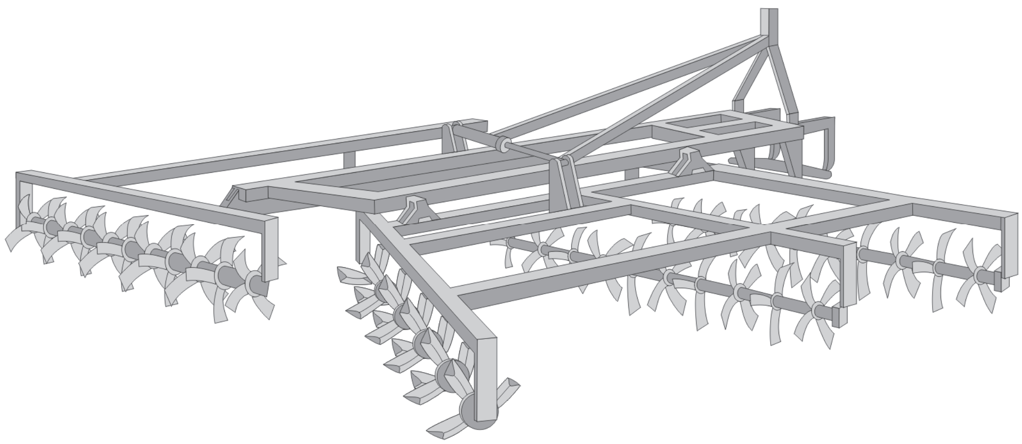


Figure 12. Schematic diagram of radial blade harrow (Peruzzi and Sartori, 1997).

Rolling harrows

This new implement has been developed by researchers at the University of Pisa (Italy) (Peruzzi et al., 2005). Partly inspired by other innovative implements, such as the basket weeder (Bowman, 1997), this harrow is manufactured in Italy by MIPE-Viviani SPA. Due to its design, this implement can effectively control weeds even in bad soil conditions by tilling superficially. This harrow is equipped with spike discs placed at the front and cage rollers mounted at the rear. Ground-driven by the movement of the tractor, the front and rear tools are connected by a chain drive with a ratio equal to 2 (Figure 13).

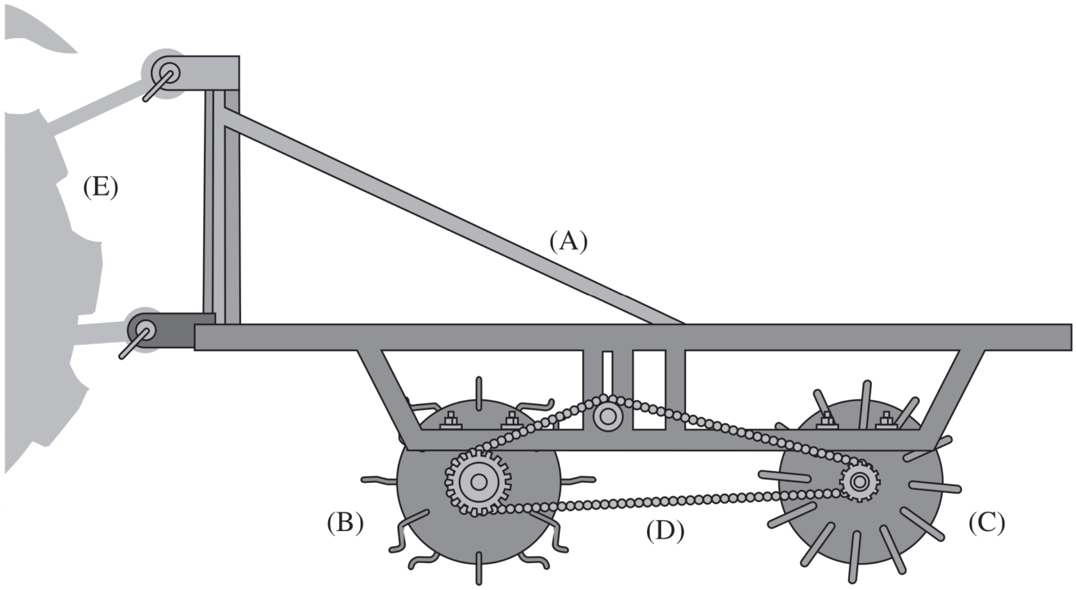


Figure 13. Schematic diagram of the rolling harrow: (A) frame; (B) front axle equipped with spike discs; (C) rear axle equipped with cage rollers; (D) chain drive; (E) three points hitch (Peruzzi et al., 2005).

The discs and the rollers can be arranged differently on the axles. They can be tightly spaced to superficially till the whole area for seedbed preparation and non-selective mechanical weed control (Figure 14). Alternatively, they can be spaced to precisely cultivate between crop rows (Figure 15) (Peruzzi et al., 2005).

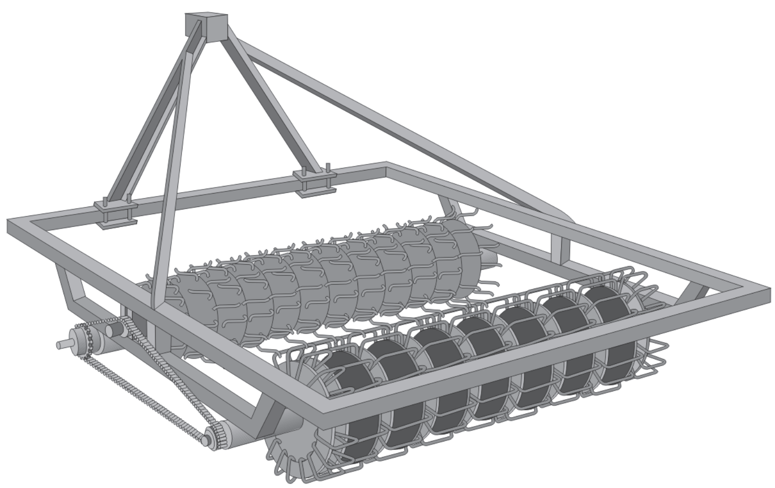


Figure 14. Tight spacing of the tools of the rolling harrow for seedbed preparation and non-selective treatments (Peruzzi et al., 2005).

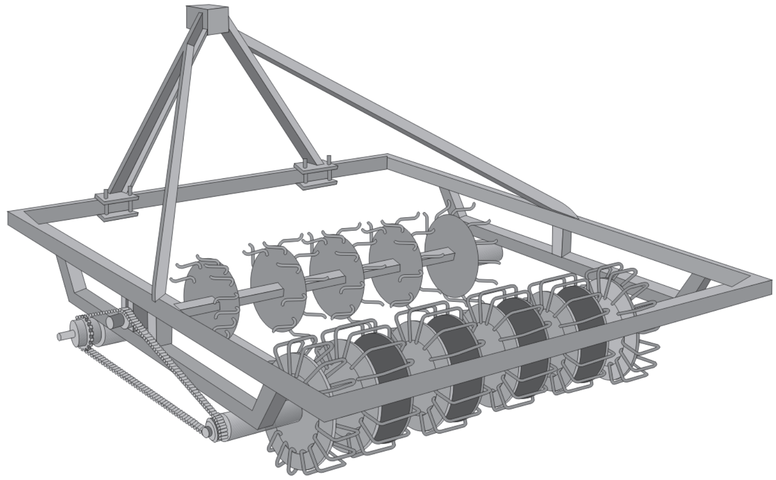


Figure 15. Spacing of the tools of the rolling harrow to precisely cultivate between crop rows. (Peruzzi et al., 2005).

The action of the rolling harrow is characterized by the passage of the spike discs that till the top of the soil. Behind them are the cage rollers that work at a higher peripheral speed because the front axle drives the rear axle (ratio of 2), tilling and crumbling the surface of the soil. These two actions provide an excellent level of control.

PTO powered machines

PTO powered machines are rear-mounted to the tractor and equipped with tools that have a generally high speed of blade rotation, irrespective of the tractor speed. These implements produce a soil that is crumbled, stirred, loosened and almost pulverized before planting. In this category of implements, it is possible to find both rotating harrows, equipped with a series of pairs of counter-rotating tools such as blades and teeth (Figure 16) that rotate on the vertical axle (Figure 17), and rotating hoes, equipped with only one rotor revolving on the horizontal axle to which are attached a series of discs bearing usually 4-6 tools (Figure 18) such as conventional curved blades, L shape blades, and teeth (Figure 19). Both implements are usually equipped with rollers (basket, spike, cage, packer, spiral, etc.) placed at the rear, which facilitates the adjustment of the working depth when used as a depth wheel. These rollers also crumble the topsoil and level the soil surface (Figure 20). For the latter, rotary tillers are often equipped with a levelling bar, either placed in the front or at the rear. Furthermore, both types of implements may be equipped with a series of tines placed in the front that acts as a subsoiler (Figure 21) to till and to structure the deeper layer of the soil while removing the sole created by the use of the mouldboard ploughs or of other tillage equipment (ASABE, 2009b; Barthelemy et al., 1987; Peruzzi and Sartori, 1997).

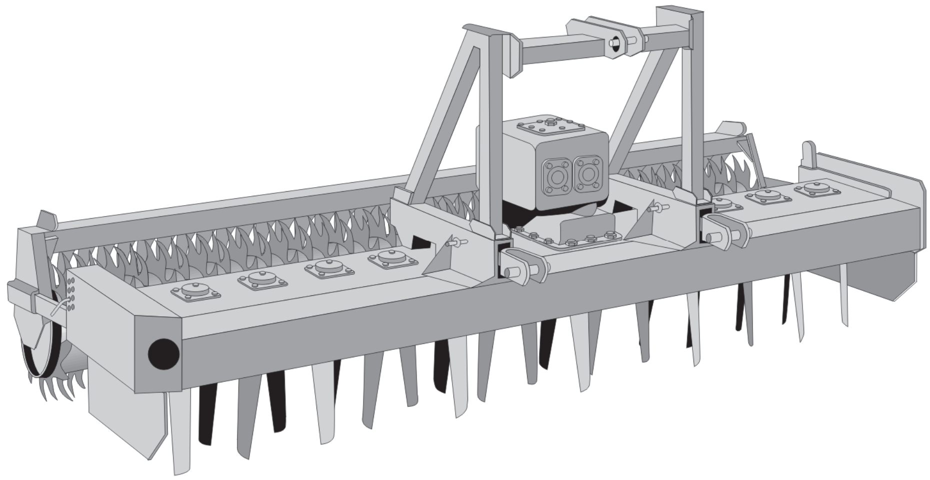


Figure 16. Schematic diagram of PTO powered rotating harrow (Peruzzi and Sartori, 1997).

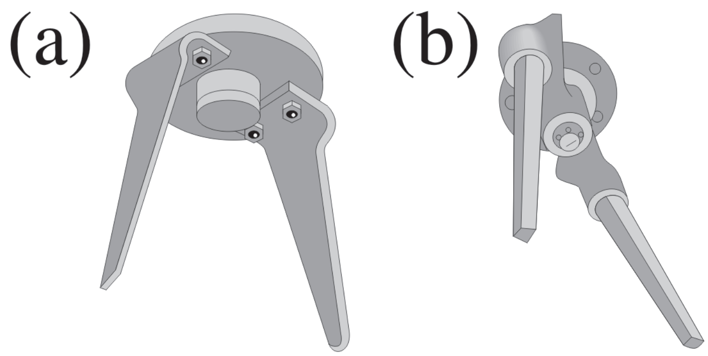


Figure 17. Tools mounted on the rotors of the PTO powered rotating harrow: (a) blade tools; (b) tooth tools (Peruzzi and Sartori, 1997).

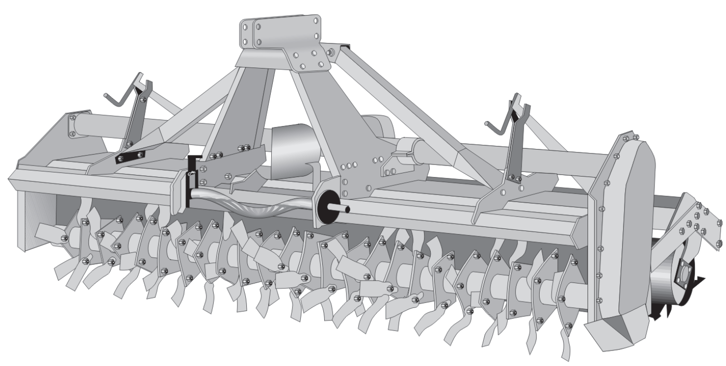


Figure 18. Schematic diagram of PTO powered rotating hoe (Peruzzi and Sartori, 1997).

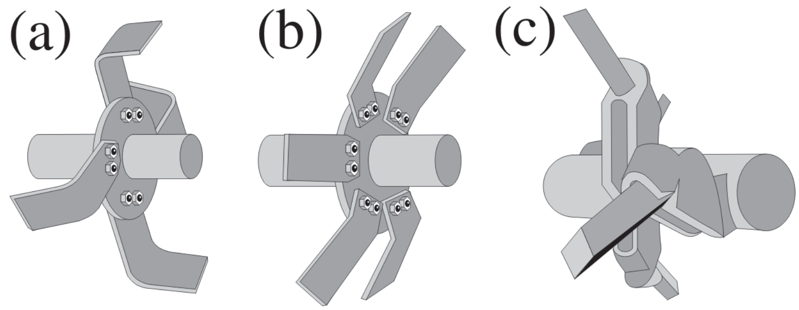


Figure 19. Tools mounted on the rotor of the PTO powered rotating hoe: (a) conventional curved blades; (b) L shape blades; (c) teeth (Peruzzi and Sartori, 1997).

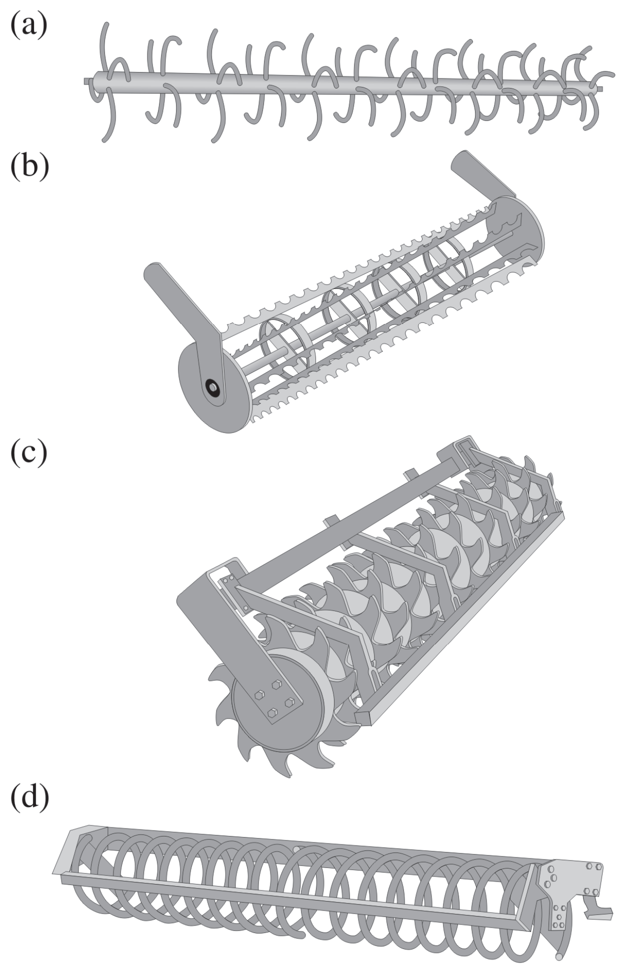


Figure 20. (a) spike, (b) cage, (c) packer, (d) spiral rolls are used with rotating harrows and hoes (Peruzzi and Sartori, 1997).

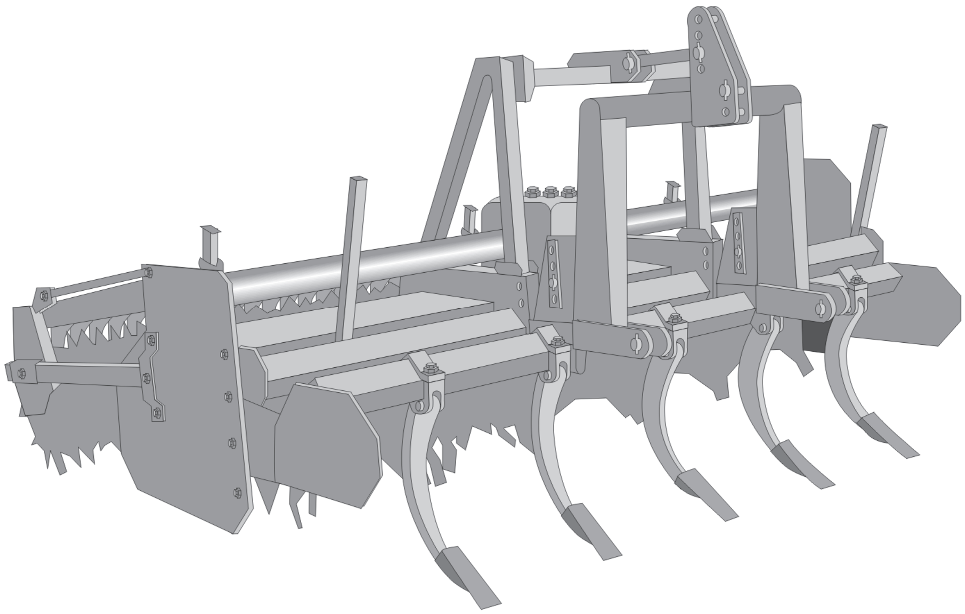


Figure 21. PTO powered rotating hoe equipped with a sub-soiler (Peruzzi and Sartori, 1997).

Following a primary tillage, these implements are normally used to do the secondary tillage to prepare the seedbed in one or more passes. In untilled soils, they may even be used to prepare the seedbed in only one pass. The working depth is generally shallow (10-15 cm) but, in some cases, it may be deeper, reaching 25-30 cm. Their effects on the soil structure are closely connected to the rotating speed of their tools and the driving speed of the tractor. Thus, the combination of a high rotating speed with a slow driving speed will produce a soil that is very loosened and pulverized while a low rotating speed combined with a fast driving speed will give a soil that is crumbled and stirred, but with an important residual aggregate size. Recent versions of these machines are often equipped with a gear that enables the operator to easily change the rotating speed of the tools to obtain different effects on the tilled soil (Barthelemy et al., 1987; Peruzzi and Sartori, 1997).

Rotary harrows control emerged annual weeds extremely well by uprooting, shredding, and burying them in the soil. However, these implements have no effects on the potential weed flora which they actually stimulate into germinating following the stirring of the soil. Compounding the problem, they can also bring up weed seeds that were in the deeper layers of the tilled soil, increasing potential weed emergence. Moreover, the rotary implements can increase perennial weed infestations by cutting their vegetative and reproductive structures, causing their multiplication. For this reason, in cropping systems relying exclusively on physical weed control, the use of PTO powered machines to perform secondary tillage, and especially false seedbed technique, should be avoided (Bàrberi, 2002; Mohler, 2001; Peruzzi and Sartori, 1997).

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Mechanical weed control in cereal crops in Eastern Canada

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Mechanical weed control in cereal crops in Eastern Canada is a well established practice and weeds are generally very well controlled. Two types of cultivators are commonly used to remove weeds from cereal crops; the rotary hoe and the spring tine harrow. In a research project conducted to determine wheat tolerance to cultivation at various growth stages, the rotary hoe was identified as being the most selective cultivator when compared with the spring tine harrow. The rotary hoe did not decrease yield at any of the crop growth stages while cultivation with the spring tine harrow caused some damage to wheat at the 2 leaf growth stage. In this research project, cultivation with either cultivator decreased wheat population but did not affect yield. Currently, producers are at the stage where they need tools to support their decision-making process in order to determine whether weeds need to be controlled in their cereal fields.

Introduction

Cereals were cultivated on 875 000 ha in Eastern Canada (provinces East of Manitoba) which represents 5,6 % of the total area under cereal cultivation in Canada and accounts for 8,6 % (30 000 000 tons) of the Canadian production (Statistics Canada, 2007).

Beginning in the early 1990's, mechanical weed control in cereals gained popularity in Eastern Canada (Coulombe, 2002; Coulombe and Douville, 2000; Douville, 1993; Douville and Jobin, 1993; Douville and Jobin, 1995; Douville *et al*., 1995; Leblanc, 2008; Lemieux and Cloutier, 1994).

The two most common cultivators used in cereal crops are the rotary hoe and the spring tine harrow. Both types are used broadcast, meaning over the whole field, including over the crop, regardless of whether the crop is seeded in rows or broadcast seeded. These cultivators are selective at the pre-emergence stage because the crop seeds are usually planted deeper than their working depth. At post-emergence stages, the selectivity is provided by the crop being better rooted compared with weeds which are usually smaller or less well rooted in their early growth stages (Cloutier *et al*., 2007). Thus, the crops tolerate more easily the pulling and burying effects of the cultivators.

Besides their weed control benefits, cultivators can also be useful in breaking the soil crust which can improve crop emergence. Rotary hoeing and spring tine harrowing can also improve soil aeration and decrease or prevent soil moisture loss by breaking soil capillarity by loosening the soil (Blake and Aldrich 1955; Buhler *et al*. 1995). These cultivators might also promote organic matter mineralization, thus increasing the nutrients availability to the crop (Gilbert *et al*., 2009; Souty and Rode, 1994).

Rotary hoe

The rotary hoe has sets of spiked wheels (available in 3 to 12 m width (Bowman, 1997)) pulled by a tractor driven at a speed of 10 to 20 km h^{-1} (Cloutier *et al*., 2007). There are two sets of ground driven wheels; one in front that throws the soil and one in back that pulls out or buries the remaining weeds (figure 1). Each wheel has about 16 spokes with spoon-shaped tips (figure 2). Rotary hoes, as most field cultivators, need to be set parallel to the ground to achieve their greatest efficacy. The optimal depth of work in the soil varies between 3 to 5 cm. The cultivation depth is function of soil texture and structure and can be changed by adding weight on the cultivator or by varying the speed of operation. The height of the tool bar together with the strength exerted by the springs determines the ground pressure of the hoe wheels. This adjustment is usually controlled by setting the position of the tractor's three-point hitch. In heavy or crusted soil, adding weights to the tool bar may be necessary in order to achieve enough down pressure to adequately till the soil. For fields with crop residues, there are high-residue models with longer arms attaching the second set of wheels which prevents jamming (figure 1b).

Figure 1. Standard model of rotary hoe (a) and high-residue model for fields with residues (b).

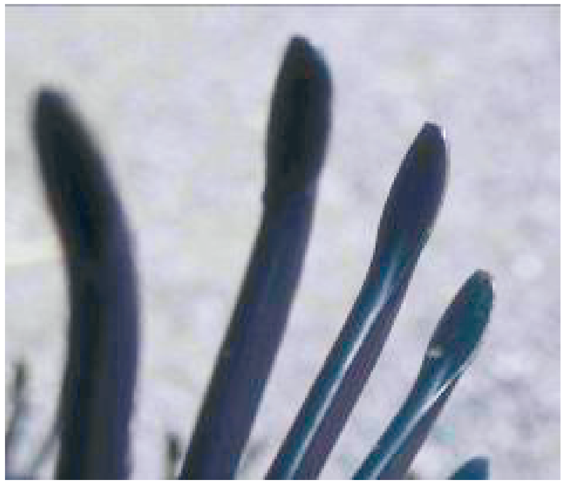

Figure 2. Rotary hoe spoon-shaped tips.

Spring tine harrow

The spring tine harrow consists of several sets of fine flexible tines mounted on floating sections (figure 3). Those flexible tines vibrate in all directions and destroy weeds by pulling or burying them. The floating units must be set parallel to the ground to achieve optimum efficacy. The harrows are available in widths varying from 3 to more than 20 m and can be used at speeds of 8 to 15 km h^{-1} (Cloutier *et al*., 2007). There are several European models and even a Canadian model made in Québec. The intensity of weed control can be adjusted by changing the working soil depth (by adjusting depth wheels on the harrow if present (figure 4a) or with the three-point hitch if there are no depth wheels) or by modifying the tines angle (figure 4b) and driving speed. Generally, the intensity of weed control will increase with tines angle (figure 4c). Reducing the speed of the spring tine harrow will decrease weed control but it will also lessen crop damage.

Timing of operation

A cultivation with the rotary hoe or the spring tine harrow can be done prior to crop emergence in order to control the initial flush of weeds that usually emerge at the same time as the crop (Cloutier and Leblanc, 2001). Annual weeds are most sensitive to disturbance at the white thread stage (figure 5) which usually refers to the conditions where the weeds have germinated but have not yet emerged from the soil. Pre-emergence cultivation takes advantage of the difference in seed size and depth of emergence between crop and weed seeds. Most weed seeds are smaller than crop seeds, and they germinate closer to the soil surface than the crop. At these early stages, breaking contact between the tiny roots and the soil will kill most weed seedlings while not disturbing the cereal seeds. The goal of the pre-emergence mechanical weed control is to provide the greatest possible initial advantage for the crop over the weeds. These implements can also be used post-emergence, in the early growth stages of the crop until the beginning of tillering.

Figure 3. Spring tine harrow with two floating sections, one on each side of the Rabe Werk bar with the support foot.

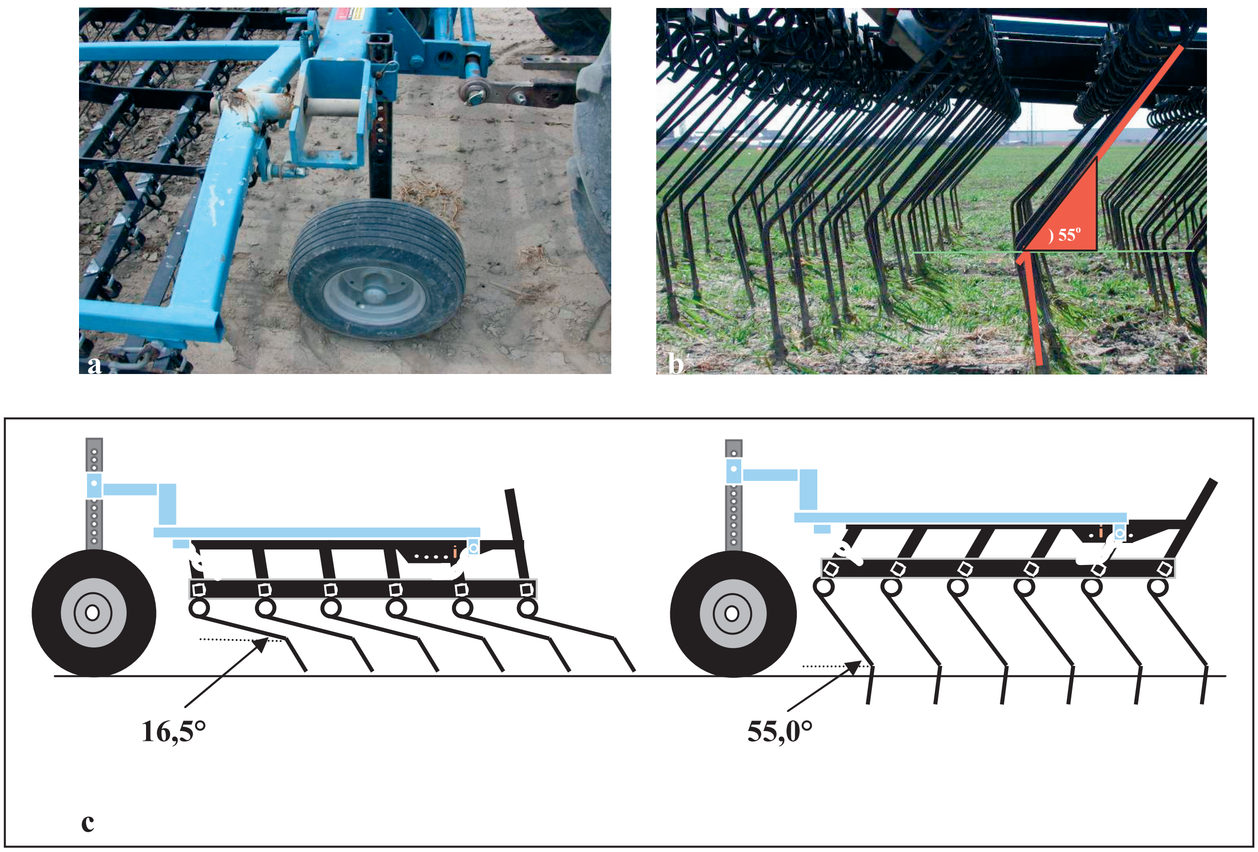

Figure 4. The intensity of weed control with the spring tine harrow can be modified by changing the depth wheels height (a) or by adjusting the tine angle (b and c).

Figure 5. Examples of the white thread stage of weeds.

Selectivity

Selectivity is defined as the ratio of weed control over crop damage (Rasmussen, 1991). High selectivity means that it is possible to control weeds with minimal risks of crop damage and yield reduction. However, in most situations, cultivator selectivity will be a function of several factors, withstanding the tractor and cultivator's adjustments themselves, such as: weeds growth stage, crop growth stage, soil texture, soil structure, soil humidity and crop health. As soon as weeds develop beyond their most susceptible stage, these cultivators' selectivity decreases, thereby increasing the risk of crop damage. Seed unearthed, uprooted seedling and/or crop burial are the main forms of crop damage that can be observed after rotary hoeing or spring tine harrowing (figure 6).

Figure 6. Examples of crop damage that was caused by cultivating with a spring tine harrow: crop burial (a), uprooted seedlings (b), and seeds unearthed (c).

Cereal growth stage susceptibility

A two year study was conducted in Québec to determine the susceptibility of durum wheat to cultivation at different growth stages (Leblanc and Cloutier, 2004). The cereal growth stages were: pre-emergence, first leaf emerged, first leaf unfolded, 2 leaves unfolded, 3 leaves unfolded plus 1 tiller, 2 tillers and stem elongation; corresponding respectively to 07, 10, 11, 12, 13-21, 22, and 30 on the Zadoks scale. This experiment was done under weed-free conditions in order to avoid confounding the effect of weed interference with crop damage caused by the cultivations. Each year, one experiment was established for the rotary hoe and one for the spring tine harrow.

In general, rotary hoeing did not decrease wheat population at harvest: 293 plants m^{-2} (cultivated) vs 310 plants m^{-2} (not cultivated). It did not reduce yield at any wheat growth stage: 4,4 t ha^{-1} (cultivated) vs 4,5 t ha^{-1} (not cultivated). There was no significant difference in grain moisture, specific weight and 1000-grain weight between any of the treatments cultivated once with the rotary hoe at various growing stages and the control treatment without cultivation.

Spring tine harrowing did cause some detrimental effects on wheat. In our study, the 2-leaf growth stage (Stage 11 on Zadoks scale) was very susceptible to harrowing. At this stage, wheat population was reduced by up to 45% and yield decreased by 16% while grain moisture increased by 1,5%, indicating a decrease in maturity. The treatments that received one cultivation only with the spring tine harrow at pre-emergence, at the 1-leaf stage or at stages after the 2-leaf stage, were not significantly affected: 4,3 t ha^{-1} (harrowed) vs 4,0 t ha^{-1} (not harrowed). At the 2-leaf stage, wheat seedlings were less well rooted and easier to bury. To decrease the risk of crop damage, cultivation intensity with the spring tine harrow can be reduced by decreasing the working depth and by decreasing the tine angle. This adjustment worked in a sandy soil but not in a clay soil because of the presence of clods in the heavier soil. Rootlets of the crop seedlings were firmly bound to the clay clods and they were severely damaged when the tines broke the clods.

Number of cultivations

Three or four cultivations performed with the rotary hoe did decrease wheat population by up to 29% but one to four cultivations had no effect on wheat yield (Leblanc and Cloutier, 2004). However, two cultivations increased grain moisture by 1 to 2%, indicating that they slightly delayed crop maturity.

Wheat population decreased between 22 to 45% when wheat was cultivated more than once with the spring tine harrow (Leblanc and Cloutier, 2004). Yield was not affected, except when one of the cultivations was done at the 2-leaf stage. In general, grain moisture slightly increased when more than 2 cultivations were done.

Weed susceptibility

Generally, it is acknowledged that weed control efficacy of the rotary hoe and of the spring tine harrow decrease as weed seedlings develop (Cloutier and Leblanc, 2001). Weeds are generally sensitive and easy to control up to the following growth stages: 2- to 4-leaf for the dicotyledonous and the 1- to 2-leaf for monocotyledonous (Cloutier et al., 2007).

Decision management

It may not be economically worthwhile to cultivate when the likelihood of crop yield losses by weed interference is minimal. Such situations can occur when weed density is low and/or when crop stand and establishment makes the crop very competitive. For example, harrowing at the first tiller stage was compared with no cultivation in an on-farm experiment in 2007 and 2008 in south-western Québec (Maryse Leblanc, unpublished data). At the end of the season, there was no difference between wheat yield, grain moisture, specific weight, 1000-grain weight, or grain protein content. In this situation, the decision not to cultivate would have been appropriate since no yield reduction was observed. However, more weeds (twice as many in 2007, and 1.2 times as many in 2008) were observed in the non-cultivated treatment but they did not produce seeds prior to cereal harvest.

The odds of the cereal crop not needing any cultivation are more likely to occur when all the factors involved in the cropping management system are optimised to favour the crop, making it more competitive against weeds. Some of the factors favouring the crop are: optimum seeding time, increase seeding rate, row spacing, choice of amendments, fertilizer placement, crop rotation, crop variety, etc.

Conclusion

Mechanical weed control in cereal crops in Eastern Canada is a well established practice and weeds are generally very well controlled. Currently, producers are at the stage where they need tools to support their decision-making process in order to determine whether weeds need to be controlled in their cereal fields. These tools are under development but mechanical weed control is one factor in cereal crops management system.

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Mechanical weed control in pulse and cereal crops:

Is there a fit in large-scale western Canadian agriculture?

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Mechanical weed control is not widely practiced by Canadian Prairie producers since the majority have adopted a no-till system. However, there has been a steady increase in the number of organic farms, particularly in the province of Saskatchewan. Since organic farms in the prairies are typically larger than in other parts of Canada, mechanical weeders need to be relatively large and/or able to operate at fast working speeds. The Canada-Saskatchewan Agri-Food Innovation Fund, initiated in 1995, supported a number of mechanical weed control studies in a range of annual crops. Despite this research effort, post-emergence mechanical weed control has not been widely adopted by prairie organic producers. Few tools can satisfy requirements such as high work rates, good weed control and conservation of surface crop residues; however, a min-till rotary hoe has shown potential to satisfy most of these requirements under prairie conditions. A long-term study at Scott, SK indicates that in-crop mechanical weed control combined with other cultural practices can prevent the buildup of weed seedbanks and maintain weed densities at manageable levels over time. Investment in engineering

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research and development of innovative tillage tools are required to meet the needs of the growing organic industry in the Canadian Prairies.

Additional Keywords: pre-plant tillage, post-emergence tillage, harrowing, cultivation, rotary hoe.

Introduction

Environmental, technological, and economic factors in the past twenty years led to one of the most dramatic changes in prairie crop production practices since the soils were broken over 100 years ago. No-till, which was restricted to about 16% of the Canadian cropped area in 1996, is now practiced on 46% of the total area, according to the most recent census reports (Statistics Canada 2006). This change has happened mainly in the Prairie Provinces. Weed survey data in the early 2000's indicate that adoption of no-till is higher in the brown and dark brown soil zones, with highest adoption in Saskatchewan (Leeson and Thomas2007). Statistics Canada (2006) that Saskatchewan led the Prairie Provinces with no-till methods practiced on 60.2% of the seeded land, up from 38.7% in 2001. Summer fallow area in Saskatchewan has dropped since 1998 by 50% to 2.1 million hectares in 2007 (Saskatchewan Ministry of Agriculture 2007).

Although no-till is popular, organic farming is also expanding in Western Canada. In 2005, there were 560,000 hectares of land in certified organic production in Canada, 85% of which is in the Canadian Prairies (Macey 2008). Saskatchewan is also a leader in the adoption of organic production with about 50% of Canada's total certified organic hectares.

Two distinct trends in prairie cropping practices now exist. The first is a widely adopted no-till system that combines herbicide and cultural weed management with little or no mechanical intervention. The second is a cultural / mechanical weed management based system which does not allow the use of synthetic pesticides. Both systems share the common goal of producing nutritious food while protecting soil and water resources.

Organic Farming Practices on the Prairies

While the Prairies account for over 80% of land devoted to organic production in Canada, they include about 45% of all organic producers (Macey 2008). Organic farmers on the Prairies tend to have relatively large farms growing mainly cereal, oilseed and pulse crops, while those in central Canada and the coastal regions tend to be smaller fruit and horticulture crop producers. It is not uncommon to find Prairie growers that have more than 1000 to 2000 ha in organic production (Beckie 2000).

Due to the large farm size, mechanical weed control needs to be quick and efficient as possible. Large implements that can cover a large land base in a short period of time are required. Organic producers rely heavily on crop rotation and cultural practices such as delayed seeding to manage weeds (Frick 2005); however, tillage is an important component of their weed management program (Buhler 2005). Surveys of organic farmers indicate that all practice some sort of tillage (Beckie 2000) and most rate summer fallow, fall and spring pre-seeding tillage as important means of weed control (Buhler 2005).

Buhler (2005) reported that the majority of tillage implements employed by organic growers for fall and early spring tillage are non-inversion tillage implements such as heavy and light duty field cultivators, and rod-weeders. Tandem discs and other disc implements were commonly used for the termination of green manure crops with only one producer out of 63 surveyed using a moldboard plow for incorporation. Forty percent of organic producers conduct fall tillage after harvesting a crop while about 50% spring till prior to seeding (Buhler 2005). Twenty-two percent of producers employed both fall and spring tillage. The most common implements used for fall tillage were: heavy duty cultivators with spikes (27%); harrows (21%); light duty field cultivators (19%); tandem disc (17%); heavy duty cultivators with sweeps (10%); and rod-weeders or rotary harrows (6%). The most common implements used for pre-seeding spring tillage were: harrow or harrow-packer combinations (30%); light duty field cultivators (26%); heavy-duty cultivators with sweeps (24%); rod-weeders (10%); heavy duty cultivators with spikes (5%); tandem disc (3%); or rotary harrows (2%).

Pre-seeding and pre-emergence tillage

Spring tillage can warm the soil and stimulate weed seed germination. Prior to the introduction of selective herbicides, secondary tillage in combination with delayed seeding was used to control wild oat (*Avena fatua* L.) in cereals although this usually was associated with a yield penalty (Canada Department of Agriculture 1959). Despite the yield reduction, pre-seeding tillage and delayed seeding remain the only possible weed control practices for the production of small seeded organic crops such as flax (*Linum usitatissimum* L.) since they are unable to tolerate post-emergence tillage (Carr et al. 1997). Rowland et al. (2006) reported that pre-emergence tillage and delaying seeding until late June reduced weed biomass and produced satisfactory yields of organic flax (Fig. 1).

The concept of selectivity is important in determining whether mechanical weed control will be successful. Selectivity is defined as the ratio between weed control and crop injury (Rasmussen, 1990). Yield losses can occur if crop injury exceeds the weed control benefit. Tillage between seeding and crop emergence can be highly selective, particularly with large seeded crops that are deep seeded (Johnson and Holm 2010). A rod-weeder is an implement that can maintain a constant tillage depth and has commonly been used for pre-emergence weed control on the prairies (Fig. 2) Seeding field pea (*Pisum sativum* L.) at a depth of 7.5 cm in mid-May followed by pre-emergence rod-weeding was effective in reducing weed biomass and producing yields that were 80% of the herbicide check (Johnson and Holm 2010).

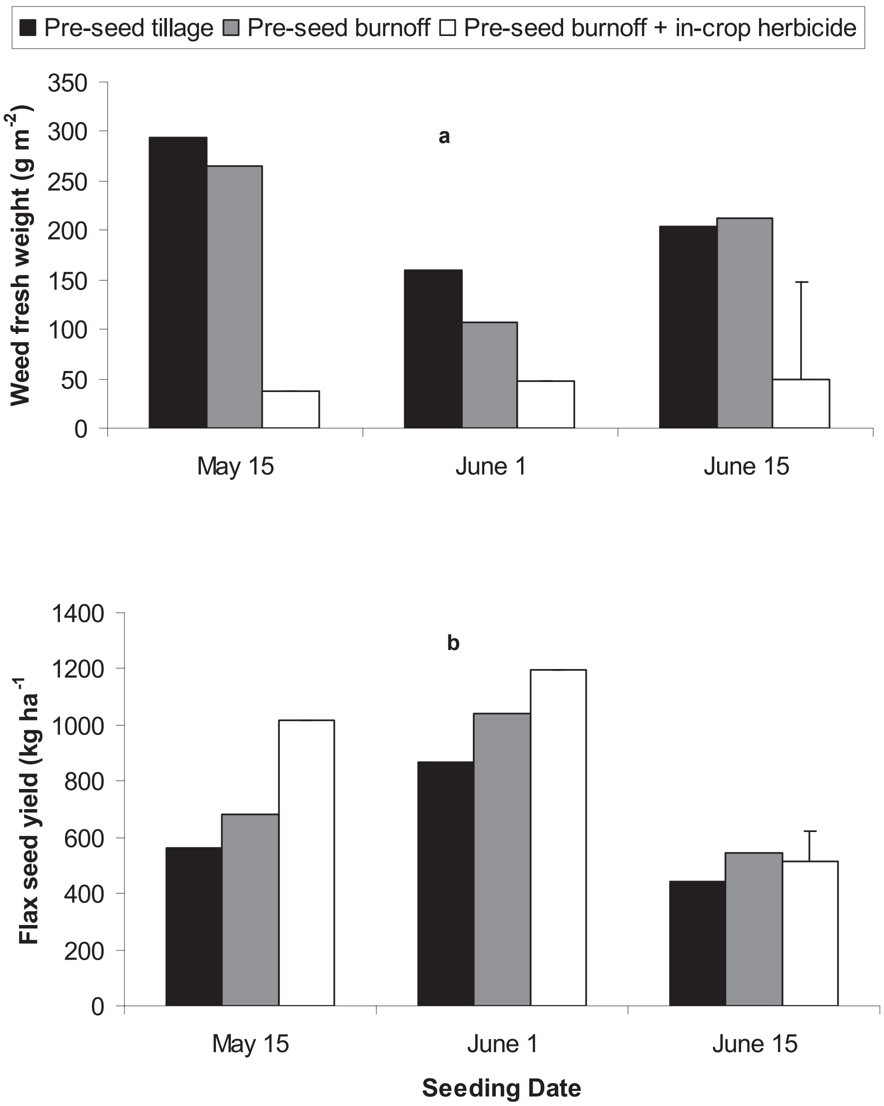

Figure 1: The interaction of weed control (pre-seeding tillage, pre-seed glyphosate application, and pre-seed glyphosate / in-crop herbicide application) with seeding date on weed biomass (a) and seed yield (b) of flax. Error bar represents the $LSD_{0.05}$. Adapted from Rowland et al. (2006).

Figure 2: Pre-emergence tillage with a rod-weeder (Photo credit: E. Johnson)

Post-emergence tillage

Although there has been a fair amount of research on post-emergence mechanical weed control on the Prairies (Lafond and Kattler 1992; Kirkland 1994; Johnson 2001; Shirtliffe and Johnson, 2006), the practice has not been widely adopted by organic producers. Beckie (2000) reported that 52% of organic growers used post-emergence harrowing while a more recent survey found that only 16% of organic fields received a post-emergence harrowing operation (Buhler 2005). Some of the reasons for limited producer adoption of post-emergence tillage includes: inconsistent selectivity for various crops; lack of specific recommendations; need for multiple passes to maximize weed control and yield responses; and a lack of specialized equipment, in particular equipment that will work in the presence of crop residues.

Most cereal crops have reasonable tolerance to post-emergence harrowing. The yields of barley (*Hordeum vulgare* L.) and spring wheat (*Triticum aestivum* L.) grown under weed-free conditions were not reduced by a single harrow pass conducted at three different crop stages in a 12-year study conducted at Indian Head, SK. (Lafond and Kattler, 1992). Kirkland (1994) reported that multiple post-emergence harrow passes reduced wild oat panicles and fresh weight in spring wheat in two years out of a three-year study. However, spring wheat yield was improved in only one year of the study. Three to four passes were required in order to obtain a 40 to 80% reduction in wild oat fresh weight. Johnson and Shirtliffe (2007) reported that tame oat (*Avena sativa* L.) is quite tolerant to post-emergence harrowing, which contradicts provincial recommendations (Saskatchewan Ministry of Agriculture 2006).

Post-emergence tillage has a positive weed control effect but selectivity is generally low due to a negative soil covering effect on crop plants (Rasmussen 1990). Crop tolerance to post-emergence harrowing is dependent on two factors: the crop's ability to resist soil covering and to recover from soil covering (Hansen et al. 2007). The ability to resist soil covering is assessed by visually estimating percent soil cover or by the use of digital imagery to quantify soil cover (Rasmussen et al. 2007). Crop yield is the common parameter used to assess a crops ability to recover from soil covering. Studies by Shirtliffe and Johnson (2006) on post-emergence harrowing in cereals indicate that crops were able to resist soil covering at later leaf stages (based on visual burial estimates); however, they were more able to recover from harrowing at early growth stages. In weed-free plots, yields of barley and oats declined when harrowing was conducted at the six-leaf stage, compared to the two- and four leaf stages. Field pea exhibited a greater ability to resist soil covering at later growth stages, although its ability to recover from soil covering was similar at all growth stages under weed-free conditions (Table 1). In weedy conditions, field pea yields were higher when harrowing was conducted at early growth stages, illustrating the importance of early weed removal.

Table 1: Effect of post-emergence harrowing conducted at different field pea development stages on % soil covering in weed-free conditions, and crop yield under weed-free and weedy conditions. Mean of 6 harrow passes and 3 harrow aggressiveness settings. Unpublished data from Johnson (2004, 2006).

Timing of Post-emergence Harrowing	Weed-free % Soil Cover	Weed-free Yield (kg ha^{-1})	Weedy Yield (kg ha^{-1})
3 above-ground node stage	54%	1882	1261
6 above-ground node stage	43%	1883	1133
9 above-ground node stage	29%	1921	1090
$LSD_{0.05}$	3%	101	130

Attempts are being made to improve the selectivity of post-emergence harrowing; however, there are limitations. Duerinckx et al. (2005) stated that minimizing crop injury from post-emergence harrowing is achieved by low travel speed, a thin tine, and a trailing or vertical tine orientation to maintain constant depth and distance from crops. On the other hand, weed control is improved by high speed, deep tine penetration, a thick tine, and a forward leading orientation. Finding a balance between the two is the key to optimizing results from post-emergence harrowing. Johnson (2001) reported that there were minimal selectivity differences between a rotary or rigid tine harrow in field pea (Fig. 3); however, selectivity could be improved by harrow adjustment, particularly with the rigid tine harrow (Fig. 4). A highly aggressive setting with the tines oriented 10º backwards increased wild oat biomass due to a reduction in field pea density. Orienting the tines 45º backwards resulted in less crop injury without sacrificing a significant level of weed control (Fig. 4). In a separate study, Johnson (2001) reported that improvements in selectivity could also be made by changing the tine orientation in a flexible tine-harrow (Fig. 3).

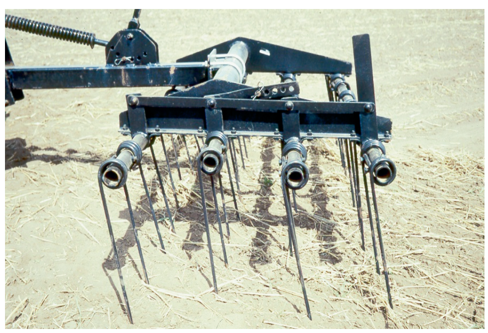

Figure 3: Rigid tine harrow (top left), flex-tine harrow (top right) and a rotary harrow (bottom). (Photo credits: rigid-tine and flex-tine harrow: E. Johnson; rotary harrow: S. Brandt)

A challenge for organic growers on the Canadian prairies is to conduct pre- and post-plant tillage and maintain surface crop residues. The maintenance of surface crop residues is necessary to reduce potential wind and water erosion. Early publications recommended that post-emergence harrowing be conducted only on summer fallow crops as harrow plugging from crop residue can result in poor weed control and excessive crop damage (Canada Department of Agriculture 1936).

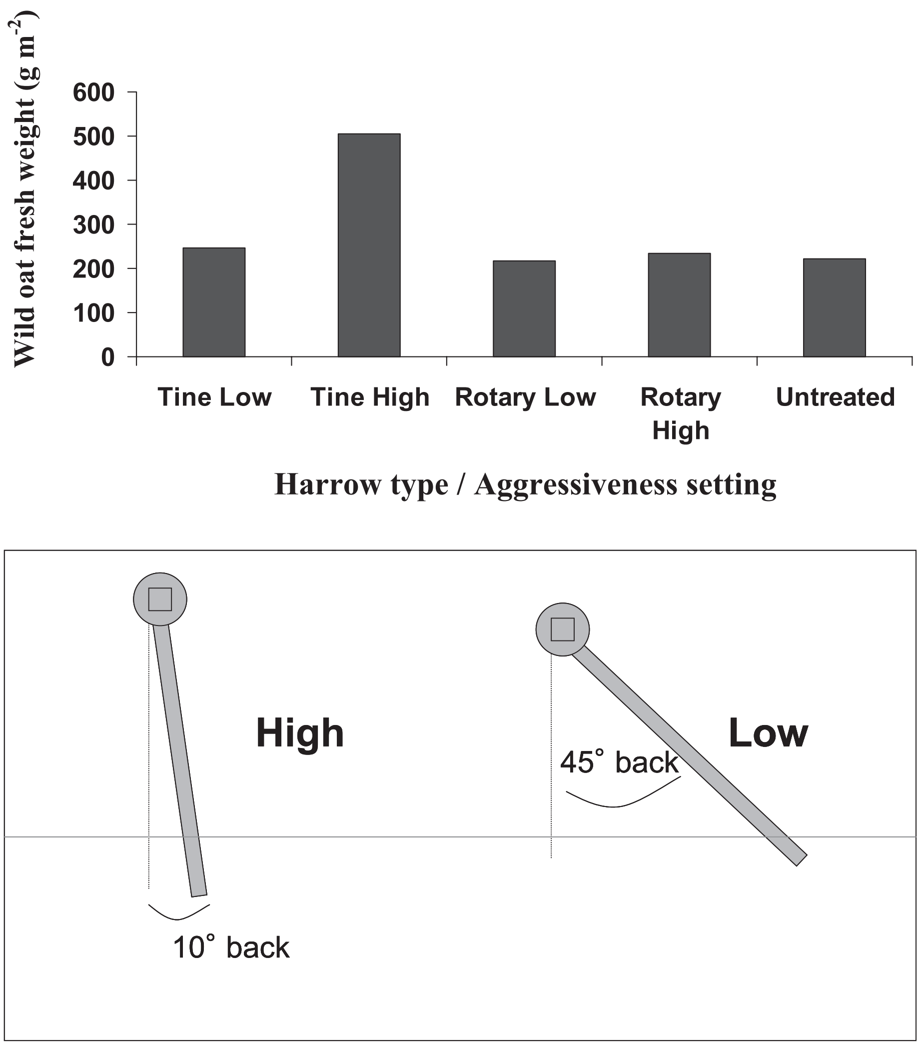

Figure 4: The effect of harrow setting on wild oat biomass in field pea (top). The bottom diagram illustrates the orientation of a high aggressive and a low aggressive tine setting. Adapted from Johnson (2001).

One implement that may provide weed control in field crops in the presence of crop residues is the min-till rotary hoe (Shirtliffe and Johnson 2006; Johnson 2007). Extended rear arms in a min-till rotary hoe creates two separate gangs of wheels, whereas a conventional rotary hoe has a tightly spaced single row of wheels (Fig. 5). The separated gangs reduce plugging with crop residue. The rotary hoe can be used pre- or post-emergence in many crops (Buhler et al. 1992; Forcella 2000; Leblanc and Cloutier 2001). It is not a common implement on the prairies, although a small percentage of organic growers use it for weed control (Beckie 2000). The rotary hoe is not effective on large-seeded weeds such as wild oat but it can effectively control small seeded weeds such as wild mustard (*Sinapis arvensis* L.) and green foxtail [*Setaria viridis* (L.) P. Beauv.] (Shirtliffe and Johnson 2006). Pre-emergence treatments with the rotary hoe provided adequate weed control in standing stubble and maintained surface residues even after six consecutive passes (Johnson and Shirtliffe 2009). Efficacy studies are underway in Saskatchewan to investigate the frequency and timing of rotary hoeing that will optimize weed control in field crops (Johnson and Shirtliffe 2009). The rotary hoe is operated at relatively high speeds so many hectares can be cultivated in a short period of time (Cloutier et al. 2007). This may be advantageous for the larger farms that are common to western Canada.

Figure 5: A min-till rotary hoe (left) and a conventional rotary hoe (right). (Photo credit: E. Johnson)

Inter-row cultivation is not commonly practiced on the Canadian prairies with the exception of some potato (*Solanum tuberosum* L.) and dry bean (*Phaseolus vulgaris* L.) production. Six percent of organic growers surveyed in Saskatchewan used inter-row cultivation for weed control (Beckie 2000). Most of the cereal, oilseed, and pulse crops are seeded in rows of less than 30 cm making inter-row cultivation difficult and time consuming on large acreage farms. Johnson (2001) reported modest levels of weed control and improvement in field pea yield from two inter-row cultivations. The yield-limiting factor was intra-row weeds, a common problem with inter-row cultivation (van der Weide et al. 2008).

Other mechanical weed control techniques

Equipment has been developed or modified to clip weeds above the canopy of short stature crops such as flax and lentil (Fig. 6). The clipping is done when the weeds are flowering and prior to seed development (Prairie Agriculture Machinery Institute 2003). Since the clipping is done relatively late, it does not improve crop yield; however, studies indicate that weed seed return may be reduced (Johnson and Hultgreen 2002). The long-term impact of this practice needs further evaluation.

Based on a suggestion from organic growers, mowing of cereal crops in the early growth stages was evaluated as a weed control measure (Fig. 7). Organic growers that tried this practice felt that the re-growth of the domesticated crop was faster than the weeds, which would result in a competitive advantage to the crop. This observation was not supported by field research. Wheat, oats and barley tolerated mowing up to the 4.5 leaf stage; however, weed control was erratic and crop yield was not improved (Shirtliffe and Johnson 2006). Rolling of flax with a pulse roller (Fig. 7) was also suggested as a possible mechanical weed control technique. Growers suggested that a brittle weed such as wild mustard would break while a flexible flax plant would recover. Shirtliffe and Johnson (2006) investigated this practice in a 3-year study and found that flax tolerance and weed control were not acceptable.

Figure 6: A modified wind-rower that clips weeds above crops such as flax and lentil (Photo credit: Prairie Agriculture Machinery Institute)

Figure 7: Post-emergence mowing in cereal crops (left) or rolling flax with a pulse roller (right) were not effective in managing annual weeds (Photo credit: E. Johnson)

Long-term impact of in-crop mechanical weed control

The long-term impact of in-crop mechanical weed control on weed density has not been extensively researched. The Alternative Cropping Systems Study at Scott is an 18 year project that is investigating the long-term effects of inputs and cropping diversity on the economic and environmental sustainability of farming systems (Brandt et al. 2010). The study consists of a matrix of three input levels (high, reduced, and organic) applied over three levels of cropping diversity (low diversity, diversified annual crops, and diversified annual/perennial crops). A comparison of residual weed densities in field pea, wheat, and barley grown in a high input system compared to an organic system provides some insight into the long-term impact of post-emergence harrowing. In-crop weed management is predominately herbicides and post-emergence harrowing in the high input and organic input systems, respectively. The organic system typically has higher residual weed densities; however there does not appear to be a trend for increasing weed density or variance over time in either input system (Fig. 8). The organic cropping system relies on more than just post-emergence harrowing to manage weeds. The long-term effect is the result of combined cultural and mechanical methods including higher planting densities, green manure fallow, and delayed seeding. The lack of a long-term trend in residual weed density indicates that integrated cultural and mechanical methods used in this study allow for some depletion of the weed seedbank and prevents the increase of weed densities over time.

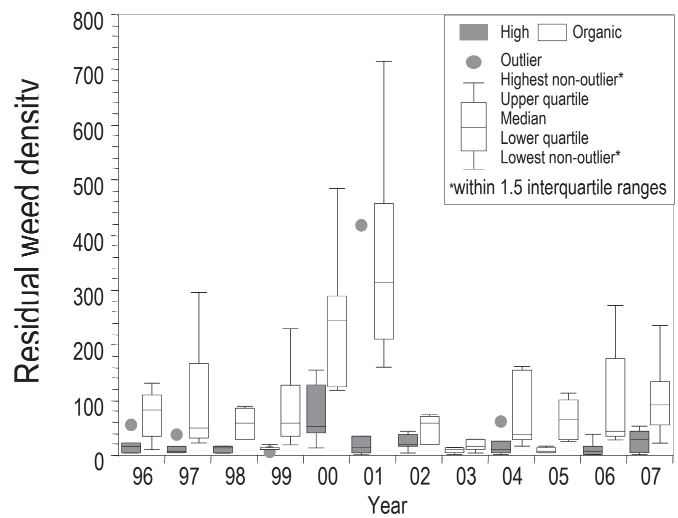

Figure 8: Temporal variation in post-treatment weed densities in high input and organic cropping systems. Herbicides and post-emergence harrowing were predominately the weed management tools in the high input and organic systems, respectively. Leeson and Thomas, unpublished data. Scott Research Farm. 1996-2007.

Conclusions

There is a place for mechanical weed control in organic agriculture in the Canadian prairies provided that it can be done relatively quickly and maintain surface residues. The min-till rotary hoe currently shows the most potential to meet these requirements. Additional engineering and machinery development is required to meet the needs of the growing organic industry. Challenges remain for weed control in small seeded organic crops such as flax and other oilseeds. Mechanical weed control should be treated as a tool which needs to be integrated with other cultural practices in order to prevent the build-up of weed seedbanks and to maintain weed densities at acceptable levels.

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The Impact of Tillage on Weed Populations and the Soil Environment

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A limited number of herbicides are registered for horticultural crops in Canada. Consequently, producers have few weed management options and use herbicides with similar modes of action repeatedly (Bell et al. 2000). Herbicides effectively control weed populations but rarely control all weeds present in the field. In many situations, weed densities have not declined after many years of intensive herbicide input and in some cases may actually be increasing in number and diversity (Ghersa and Roush 1993). Relying solely on herbicides to control weed populations may also lead to a variety of environmental and production problems. Safe and effective pesticide use is one of the most challenging research priorities and environmental challenges facing horticultural producers. As of 2002, pesticide sales had reached $1.27 billion in Canada with herbicides accounting for 80% of sales (CropLife Canada 2003). Many of these chemicals are soil applied herbicides such as atrazine, alachlor and hexazinone that are prone to movement into ground and surface water supplies. To decrease reliance on herbicides requires: (1) increased herbicide use efficiency, (2) substitution of herbicides with other weed management techniques such as tillage, or (3) redesign of the cropping system to reduce the need for herbicides (Nazarko et al. 2005).

Tillage Impacts on Weed Populations

Tillage is one of the oldest and most effective forms of weed control. A wide range of implements are available depending on the type of soil, crop grown, and crop residue levels present. Tillage impacts both the emerged weed seedlings and the weed seed bank. The impact of tillage on weed population dynamics has largely been studied in agronomic crops. However, it is likely that the impacts of tillage or the adoption of zero tillage techniques would have similar impacts within horticultural crops.

Tillage and Weed Seed Movement

Tillage operations move weed seeds both horizontally and vertically. The type of implement used and the speed traveled affects the distance weed seeds move during tillage operations. Rew and Cussans (1997) found that 84% of weed seeds moved less than 1 m horizontally from the source during cultivation and no seeds moved more than 4.8 m. The limited horizontal movement of seeds is unlikely to have a significant impact on weed spatial dynamics whereas vertical weed seed movement is likely to impact the timing, number and type of weeds emerging.

Various tillage regimes affect the vertical movement of seeds within the soil profile. Buhler and Mester (1991) found that mean depths of weed emergence were shallowest in no-till, followed by chisel and conventional tillage. In a simulated seed dispersal experiment, Yenish et al. (1996) found that 90% of seeds remained within 2 cm of the surface with no-till while chisel plough and discing placed 40% of the seeds 4 cm from the surface with nearly 100% of the seeds within the top 10 cm of the soil profile. Moldboard ploughing placed 50 to 60% of the seeds at 11-16 cm with few seeds above 8 cm. With multiple cultivations, seeds that were buried during the initial cultivation may be moved back to the surface. Cousens and Moss (1990) reported that, with a single simulated seed rain, ploughing initially buried seeds deep within the profile but after 5 years with annual cultivation the distribution of weed seeds was similar between the surface and 20 cm depths, changing little with additional tillage. With rigid tine cultivation, it took approximately 10 years to reach a stable distribution which was approximately equal to the distribution of the moldboard ploughed plots. Moldboard ploughing tends to homogenize the soil seed bank in three dimensions while reduced tillage produces denser seed banks in the upper 5 cm (Feldman et al. 1998). Generally, as tillage decreases, the number of weed seeds and weed seeds germinating near the surface increases (Spandl et al. 1998). Therefore, no-tillage fields should have a higher population of seeds on or near the surface while conventional tillage should have fewer weed seeds on the surface but more seeds spread throughout the soil profile forming a persistent seed bank.

The depth of weed seeds within the soil profile affects the number of seedlings that emerge and the timing of emergence. Most weeds in arable fields emerge from the top 6 cm of the soil profile (Cousens and Moss 1990; du Croix Sissons et al., 2000) although others may emerge from much deeper depths. Emergence number and rate tend to decline with depth (Cussans et al. 1996) with many weed species achieving optimal germination just below the soil surface. This trend does not apply to all species and some, such as cleaver (*Galium aparine* L.), have reduced emergence when seeds are placed directly on the soil surface (Boyd and Van Acker 2003). The timing of emergence is important because the competitive ability of a weed often depends on whether it emerges before, after or during crop emergence. Weeds germinating after crop emergence or the critical period for weed control tend not to have as large of an effect on yield nor will they produce as many weed seeds (Wall and Friesen 1990).

Tillage and Soil Temperature

Tillage not only moves seeds horizontally and vertically within the soil but also changes the soil physical environment directly around the seed. Soil temperature is one of the key parameters determining the timing of weed seedling germination and emergence. It has generally been observed that no-tillage soils or reduced tillage soil have lower soil temperatures than conventionally tilled soils.

While tillage affects soil temperature in many ways, the percent residue cover left on the soil following early spring cultivation has the greatest impact on spring soil temperatures (Potter et al. 1985). During the day, plant stubble or surface debris left on the surface acts as an insulator due to its low thermal conductivity. Since soil is typically darker in color than plant material and has a lower reflectivity it absorbs incoming radiation more rapidly than surface stubble which increases the soil reflection coefficient reducing the heat absorbed during the day (Johnson and Lowery 1985). During the night, surface debris reduces the emission of long wave radiation (Hay et al. 1978). Consequently, spring soils with high levels of material on the surface absorb less heat during the day and emit less heat during the night resulting in an overall decrease in soil temperatures as well as a decrease in temperature fluctuations.

Stubble or surface debris also affects winter and early spring soil temperatures in northern climates by holding more snow during the winter months which also acts as a soil insulator. Larsen et al. (1988) reported warmer winter soil temperatures and increased winter wheat survival in tall stubble systems. Benoit and Van Sickle (1991) found that soil temperatures were highest in no-till soils that had stubble during the winter months. The accumulation of snow had a greater impact on temperature than tillage regime or residue level alone. The no-till residue treatment tended to have higher temperatures in early spring and became frost free 10 to 30 days before other tillage and residue combinations. A combination of the warmer winter temperatures, earlier warming of the soil and lower heat absorption and emission impacts the survival and timing of weed seedling emergence.

The second way that tillage affects soil temperatures is by altering soil bulk density, pore space and water content which affect the transmission of energy into and out of the soil. The movement of heat through the soil depends on the thermal conductivity and volumetric heat capacity (Hay et al. 1978). Thermal conductivity is a measure of the ease with which the soil conducts or transmits heat while soil volumetric heat capacity is the amount of heat the soil must absorb or lose to produce a one degree (C) change in temperature. The ratio of these properties (thermal diffusivity) is a measure of the rate and depth of heat transfer through the soil (Hay et al. 1978). Potter et al. (1985) reported a similar soil volumetric heat capacity for a variety of tillage treatments while thermal diffusivity was significantly greater in the no-till soil than in the conventional and chisel plough systems. Therefore, they concluded that the thermal conductivity must also have been greater in the no-till system. Since thermal conductivity is affected by bulk density, pore volume and water content, any change in these factors should alter the transmission of heat. The impact of tillage on these variables is not consistent and depends on many factors including conditions during cultivation and soil type. Blevins et al. (1983) reported no difference in bulk density between no-till and conventional till while Gantzer and Blake (1978) reported higher bulk density in no-till versus conventional till. Even in the absence of measurable differences in bulk density or soil water content, tillage may alter the pore size distribution and soil matrix affecting thermal conductivity (Potter et al. 1985). Higher moisture content and increased bulk density in no-till soils could increase soil diffusivity, thus transferring heat more rapidly deeper into the soil, resulting in cooler surface temperatures than conventional tillage even when similar amounts of heat were taken in (Johnson and Lowery 1985).

Many weed species require temperature fluctuations before germination will take place. For example, Martinez-Ghersa et al. (1997) reported that redroot pigweed and barnyard grass had higher germination when temperatures fluctuated between 20 and 30ºC than when they remained constant at 20ºC. As well, Nishamoto and McCarty (1997) reported only 10% germination of goose grass (Eleusine indica (L.) Gaertn) at constant temperatures and 99% emergence with fluctuating temperatures between 35 and 20 º C. Even when different mean temperatures are not found between different tillage treatments, the fluctuation between maximum and minimum temperatures may vary. Hay et al. (1978) reported that direct drilling gave lower maximum temperatures than ploughed soil but higher minimum temperatures. A reduction in the maximum soil temperatures obtained may result in a shortened temperature amplitude.

Tillage and Soil Moisture

Soil cultivation breaks surface crusts, alters soil porosity and buries surface residue. These factors or a combination of these factors affects water infiltration rates as well as the water holding capacity of the soil. Although infiltration rates may initially be higher following tillage (Blevins and Frye 1993), most studies have found increased soil water in no-till when compared with conventional tillage (Bidlake et al. 1992; Blevins et al. 1971; Malhi and O'Sullivan 1990). Consequently, no-till soils may provide a method for conserving water during dry years but may also lead to excessive moisture in wet years.

Increased residue levels typically apparent in no-till fields affect soil moisture in several different ways. First, surface stubble or debris may increase the amount of snow kept on a field during the winter months (Benoit and Van Sickle 1991). In the spring, snow melt can greatly influence soil moisture levels. Second, soil surface debris slows evaporation from the soil surface by shading the soil from solar radiation, insulating the soil from heat and impeding the movement of water vapor from the soil to the air (Blevins and Frye 1993). It is difficult to determine if the difference in evaporation rates is due solely to surface cover or if changes in the soil physical properties also alter evaporation rates (Steiner 1989). Teasdale and Mohler (1993) reported a decline in soil moisture content during drought periods without residues compared with plots with crop residues left intact. Third, surface debris may hinder or prevent the run off of water during rainfall, increasing infiltration levels. No-tillage plots with surface residues also have higher soil porosity and infiltration rates than tilled plots which may partially explain increased soil moisture levels in no-till fields. Therefore, lower soil temperatures found in reduced tillage plots with increased crop residue may reduce weed emergence while increased moisture during periods of drought may increase weed emergence (Teasdale and Mohler 1993).

Tillage alters soil physical parameters affecting soil moisture. Infiltration rates may be affected by the size and number of pores in the soil. In conventionally tilled systems the pores are created primarily by the tillage equipment while pores are created primarily by biological processes in no-till systems (Benjamin 1993). Logsdon et al. (1990) reported that the total number of pores was often greater for no-till than for plots that were moldboard ploughed. Not only is the number of pores affected but also the continuity of the pores. It is generally acknowledged that higher bulk densities are found in no-till systems with less total pore volume. However, no-till soils tend to have a greater number of continuous earthworm channels that reach the surface (Benjamin 1993). The continuous pores contribute significantly to infiltration rates and hydraulic conductivity (Azooz and Arshad 1996). Blevins et al. (1983) reported that saturated hydraulic conductivity measurements suggest better water movement in no-tillage compared with conventional tillage. The increased water movement could result in less runoff from the soil surface.

Increased levels of soil moisture may vary spatially. Oryokot et al. (1997) reported no moisture differences at 2.5 cm between no-till, chisel till and moldboard ploughing. Conversely, Malhi and O'Sullivan (1990) reported that soil moisture in the surface layer (0-15 cm) was 7.2% greater for zero-tillage plots than conventional tillage plots. Blevins et al. (1971) also found higher volumetric soil water content in no-tillage soils to depths of 60 cm with the greatest differences occurring in the top 8 cm. Since most weeds germinate from the top 7 cm of the soil profile (du Croix Sissons et al. 2000) the increased moisture levels in this area could dramatically affect the weed population.

Variation in moisture levels between tillage types also varies over time. Soil moisture is typically lost from the root zone by surface runoff, evaporation, transpiration and percolation to depths beyond the normal root zone (Blevins et al. 1971). In the early part of the season, when the soil is not covered, the greatest water loss occurs from evaporation. As the plant canopy develops and shades the soil, transpiration becomes the most important route of water loss (Blevins et al. 1971). Therefore, tillage impacts on crop growth and development will also affect soil water content indirectly.

Timing of Tillage and Its Impact on Weed Populations

The timing of tillage affects both the timing of plant kill and the timing of vertical seed movement in the seed bank. Early spring tillage kills early emerging weeds but also brings seeds to the surface that may germinate prior to the establishment of the crop canopy. Tillage that occurs later in the spring just prior to crop planting has a shorter time frame between canopy establishment and the potential germination and emergence of seeds brought near the surface by the tillage operation. However, late spring tillage may be less effective if early germinating species are able to emerge, grow, and become established prior to the tillage operation. Ploughing directly following plant harvest may restrict seed shedding by killing early fall germinating seeds (Bostrom 1999). Early ploughing may not kill weed species that germinate late in the fall and form plant rosettes. For example, perennial sow-thistle is better controlled by late ploughing than early ploughing which allows the seeds to germinate and form a rosette (Bostrom and Fogelfors 1999).

The timing of seed movement affects weed populations. Volunteer canola seed may be induced into secondary dormancy if buried, thus forming a seed bank (Lopez-Granados and Lutman 1998). For this species, fall tillage should be avoided or delayed as long as possible to prevent the formation of a weed seed bank. For other weed species which germinate on or near the surface, seed burial may prevent germination and kill the seed. Foxtail barley (*Hordeum jubatum* L.) germinates best within the top 2 cm of the soil and seed viability may rapidly be reduced when buried below 7 cm (Best et al. 1978). For weed seeds that are viable for a short period of time, burial by a single cultivation might cause seed mortality if deep cultivation does not bring them back to the surface (Cousens and Moss 1990). Cultivation and the consequent burial of seeds that may last for extended periods may induce secondary dormancy, therefore reducing seed predation and seed death while allowing a greater number of seeds to germinate over a longer period of time.

No-till Vegetable Production

The potential of growing no-till vegetable crops has been explored in many regions of North America. Despite growing interest, wide spread adoption of no-till vegetables has not occurred primarily due to a lack of; (i) surface applied herbicides registered for vegetable crops, (ii) no-till planting equipment designed for horticultural production, and (iii) knowledge of conservation tillage methods amongst horticultural producers (Harrelson et al. 2004). Research over the past decade has shown that horticultural crops can be viably produced with reduced tillage techniques (Hocking and Murison 1989; Jackson et al. 2004). Broad scale adoption of no-till or minimum till techniques is likely to occur as our knowledge and technology continue to expand.

The adoption of minimum till techniques has some readily apparent environmental benefits such as reduced fuel consumption. Yoder et al. (2005) examined water and nutrient movement in no-till vegetable fields to determine if some of the environmental advantages observed in no-till agronomic fields also occurred in horticultural crops. He found that no-till techniques in vegetables reduced erosion by 92%, total Kjeldahl nitrogen surface movement by 83%, and reduced total phosphorus and nitrate movement. Harrelson et al. (2004) also found that no-till vegetable production maintained yields, improved quality, and improved soil moisture conservation. These results demonstrate that no-till practices can reduce overall environmental impact in vegetable crops. However, no-till could also have potential negative environmental impacts including increased nitrogen inputs required to maintain yields and increased herbicide inputs to control a changing weed population. In both cases, the problems may be overcome with appropriate management.

Of particular interest for this article is the impact of the adoption of minimum till techniques for fruits and vegetables on weed populations. In agronomic crops, many authors have discussed how a switch to reduced tillage techniques can result in increased populations of perennials, summer annual grasses, wind disseminated weeds, and biennial and winter annual species (Buhler 1995; Swanton et al. 1993; Froud-Williams et al. 1983). This shift does not always occur and depends on the location, environment, and the ability of producers to alter management techniques to address the changing weed pressures. It is safe to assume that a switch from intense and often deep tillage common in horticulture crops to minimum or no-till will have a large impact on weed population dynamics. Tillage operations move weed seeds both horizontally and vertically. While horizontal movement probably has minimal impact on population dynamics (Rew and Cussans 1997), vertical movement of weed seeds affects the timing, number, and type of weeds that emerge.

Under temperate conditions, there is a concentrated period of emergence of summer annual weeds. This is due to a variety of factors including temperature, stimulation by light, changes in soil moisture, and changes in nitrate levels. The emergence of this population of annual weeds in vegetable crops is of particular importance due to the limited number of registered herbicides for many vegetable crops. Several studies have reported that a reduction or elimination of spring tillage can reduce weed populations within the subsequent vegetable crop at least in the short term. For example, Peachey et al. (2006) found that continuous no-till planting of vegetable crops each year reduced summer annual weed density by 63-86% compared with continuous conventional tillage. The same authors also found that no-till planting reduced emergence of hairy nightshade (*Solanum sarrachoides*) and Powell amaranth (*Amaranthus powellii*) by 77-99% and 50-87%, respectively (Peachey et al. 2004). The effects of reduced tillage combined with the maintenance of residue on the soil surface can have a significant impact on weeds emerging within the crop. The extent of the reduction in weed density depends upon the type of residue, the weed species present, and the amount of residue left on the surface at crop planting (Burgos and Talbert 1996).

Residue management is a critical component of weed management in no-till systems. The first step is the production of adequate biomass to produce a consistent, thick cover on the soil surface. This is typically achieved with the inclusion of cover crops in the production system. They, in turn, impact crop yields (Wyland et al. 1996), soil quality (Hartwig and Ammon 2002), pest and disease management (Dabney et al. 2001), nutrient cycling (Sainju et al 2002; Wyland et al. 1996) and weed populations (Akemo et al. 2000). Cover crop residue impacts weed populations in a variety of ways by; (i) functioning as a barrier, (ii) altering soil conditions, (iii) releasing allelopathic chemicals, and (iv) providing habitat for weed seed predators. To achieve adequate cover, appropriate techniques must be used to kill the cover crop. On conventional farms cover crops are often killed with chemical desiccants; whereas, other implements, such as crop rollers and crimpers, are used effectively in organic production systems (Sayre 2004). Regardless of the technique utilized, the desired outcome is a consistent level of residue left on the surface. The type, determined by cover crop species, and the amount of residue left on the surface, determined by seeding rates, species, and growing conditions, will determine the level of weed inhibition obtained. For example, Jelonkiewicz and Borowy (2005) found that weed growth in vegetable crops was significantly reduced when a rye mulch 3-4 cm thick covered the soil surface at planting. Rogers et al. (2004) reported that cover crop mulches may be superior to polyethylene mulches in some ways. He found more earthworms and greater soil aggregate stability underneath cover crop mulches than polyethylene mulches.

A wide variety of reduced tillage techniques have been evaluated that maintain some of the benefits of no-till and also address its limitations. For example, Hocking and Murison (1989) used plastic mulches combined with minimum tillage techniques and reported yields equivalent to conventional tillage. The use of plastic mulches also enabled them to overcomes the slower development sometimes observed with vegetables grown in no-till soils (Hocking and Murison 1989). A second alternative is the use of strip tillage which maintains many of the benefits of no-till but allows cultivation within the crop row (Morse 1989). Swanton et al. (2004) found that carrot and onion yields were unaffected by strip tillage compared with conventional tillage. Myers et al. (2006) found that the response to strip tillage was variety sensitive but strip tillage generally led to a 20 to 30% increase in plant population and a 15 to 35% increase in vegetable yields when compared with no-till. Although effective, it is possible that tillage and removal of residue within the crop row may decrease weed control levels (Myers et al 2006). A third weed management option designed to address expected annual weed seed increases near the soil surface is the inclusion of tillage within the crop cycle. Mulugeta and Stoltenberg (1997) found that the addition of periodic tillage to no-till corn resulted in increased seedling emergence and seed bank depletion. The impact of periodic tillage or the rotation of tillage techniques is still poorly understood and should be further evaluated for vegetable production systems.

When properly managed, vegetable yields and quality with reduced tillage can be as good or better than those grown with conventional tillage (Hocking and Murison 1989). Financial returns with no-till vegetable crops can be higher even with lower yields due to reduced input costs (Jackson et al. 2004). No-till techniques are a viable alternative for vegetable growers and weeds can be adequately controlled with appropriate residue management and reduced tillage.

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Thermal weed control with the focus on flame weeding

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Many thermal weed control methods have been developed as alternatives to chemical and mechanical weed control. These include flaming, infrared radiation, hot water, steam, electrical energy, microwave radiation, ultraviolet radiation, laser treatment and freezing. Of these, flaming and to some extent infrared radiation, steam, hot water and electrocution have been used commercially. Flaming kills plants mainly by rupturing cells, which leads to tissue desiccation. Flaming provides rapid weed control, but has relatively low selectivity and no residual weed control effect. The dose-response models describing plant response to flaming treatments in terms of propane input per unit area are sigmoid in shape. The heat treatment dose must therefore be adjusted to take into consideration weed species and growth stage. Flame weeding was commonly used in the USA until the 1960s, mainly for post-emergence weed control in row crops such as cotton, soybeans and maize. The main use of flame weeding in Europe today is in organic production when mechanical methods are less effective. Flaming is used as an integral part of the weed management strategy, typically as a single pre-emergence treatment in carrots and other slow-germinating vegetable crops. Flaming is also used after crop emergence in maize, onions, brassicas and some other heat-tolerant crops and for potato haulm destruction. Flaming and hot water are sometimes used for weed control in urban areas. Flame weeding has demonstrated environmental benefits in terms of impacts on crop, soil and water, but uses more energy and releases more combustion by-products than mechanical and chemical methods. Flaming and most other thermal methods generally have high equipment costs and slow driving speeds. However, there is the potential to improve the efficacy and energy efficiency of thermal weeders. New tools for high precision flame weeding in the crop row are currently being developed. Techniques for band-steaming of weeds are also progressing and are already being introduced commercially in Scandinavia to reduce the need for hand-weeding in organic vegetable crops.

Introduction

Several non-chemical weed control options causing thermal injury to plant tissues have been developed. These include flaming, infrared radiation, hot water, steam, electrical energy, microwave radiation, ultraviolet radiation, laser treatment and freezing. Of these, flaming and to some extent infrared radiation, steam, hot water and electrocution have been used commercially.

Thermal weed control methods have the advantage that they provide rapid weed control without leaving chemical residues in the soil and water. However, several thermal methods are costly and slow, and relatively energy requiring. Moreover they do not provide residual weed control and therefore require repeated treatments.

Flaming and other thermal methods cannot serve as the principal weed control options in agricultural systems. Flaming is often used in organic farming when mechanical methods are less effective and herbicides are not an option. For example, in carrot production, flame weeding is used as a single application before crop emergence, and the rest of the weed management is carried out mechanically. Different thermal weed control methods are also used in urban areas where chemical methods are not desired or not allowed.

This paper describes various thermal weed control options that use energy to cause thermal injury to plants for weed control. Thermal weed control methods have recently been reviewed by Ascard et al. (2007).

Effects of high temperatures on plants

Heat injury involves denaturation and aggregation of cellular proteins, and protoplast expansion and rupture, which results in plant desiccation (Ellwanger et al., 1973a, b). Protein denaturation may start at 45°C (Sutcliffe, 1977; Levitt, 1980).

The effects of heat treatments on plants are influenced by several factors including temperature, exposure time and energy input. Temperatures in the range of 55°C to 95°C have been reported to be lethal for leaves and stems (Daniell et al., 1969; Porterfield et al., 1971; Hoffmann, 1989). Exposure to flame for 0.065 to 0.130 s is enough to kill leaf tissue (Thomas, 1964; Daniell et al., 1969).

Higher temperatures are more effective at causing plant damage. Daniell et al. (1969) found that the structural changes in cells were more pronounced when cellular temperature changed more rapidly, as in a flaming, compared with when the changes were gradual, as in a hot-water treatment.

Flame weeding

Flame weeding is by far the most widely used thermal weed control method. Flaming heats plant tissues rapidly to rupture cells but not to burn them. Currently, it is widely used for weed control in organic farming in Western Europe.

Usually flaming is applied as a single application for non-selective weed control prior to crop emergence in carrots and other slow-emerging row crops (Fig. 1) (Dierauer and Stöppler-Zimmer, 1994; Rasmussen and Ascard, 1995). Flaming before crop emergence followed by post-emergence mechanical weeding has been particularly useful (Melander and Rasmussen, 2001; Ascard and Fogelberg, 2008).

Figure 1. Non-selective flame weeding pre-emergence of the sugarbeet crop using a Swedish flamer with one burner per row and one common insulated cover.

Selective post-emergence flaming is also used, but less frequently, in crop rows in some heat-tolerant crops, e.g. maize (Fig. 2) and onions (Fig. 3) (Ascard, 1989). Occasionally, it is also used to control weeds on hard surfaces in urban areas and for desiccation of potato haulms prior to harvest (Fig. 4) (Laguë et al., 2001). Flaming has also been investigated for insect control in crops (Duchesne et al., 2001).

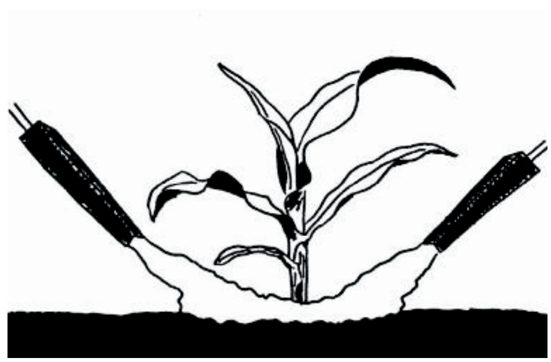

Figure 2. Selective flame weeding in maize, with one burner from each side of the row. The flames hit the small weed seedlings in the crop row and the heat tolerant lower part of the crop plant.

Figure 3. Burner setting for selective in-row flaming in onions.

Figure 4. Combined mechanical crushing of potato haulm and thermal desiccation of potato stems by flaming.

History and development of flame weeding

Flame weeding was widely used in the USA, in the 1950s and the mid-1960s (Kepner et al., 1978; Laguë et al., 2001). Open burners without covers were used for selective post-emergence flaming in crop rows e.g. cotton, maize and soybeans (Fig. 2 and 3). Covered flamers were also developed for insect control in alfalfa, and for potato haulm desiccation. Other applications included thermal defoliation in potato and cotton plants, disease and insect control in various crops. With the availability of effective herbicides and increase in petroleum costs, flaming lost popularity by the late 1970s (Kepner et al., 1978). Lately, there is a renewed interest for flaming, e.g., in the USA and Canada (Laguë et al., 2001; Leroux et al., 2001). For example, Knezevic and Ulloa (2007) evaluated agronomic crop and weed tolerance to flaming and found the greatest potential for flaming on broadleaf weeds in field maize.

Flaming was not widely used in Europe in the 1960s. Organic farmers started using flame weeding in Germany and Switzerland in the early 1970s (Hoffmann, 1989). Unlike the USA, an important use of flaming in Europe is non-selective weeding prior to crop emergence. Selective post-emergence intra-row flaming is also used in e.g. maize and onions (Ascard, 1989). Other uses of flaming are potato haulm destruction and weed control in urban areas (Rask and Kristoffersen, 2007).

Effect of flaming on weeds

Flaming kills plants mainly by rupturing cells which leads to tissue desiccation. Young seedlings are more sensitive to high temperatures (Sutcliffe, 1977). Shoot apices of young plants are more susceptible to heat damage. In older plants, the shoot apex may be protected by leaves. Regrowth of old plants following flaming may be reduced or eliminated when flames penetrate the canopy enough to kill axillary buds at lower nodes, which may be protected by surrounding leaves, leaf sheaths and petioles. Moderate flaming may only partially damage plants and their ability to regrow depends on their energy reserves, environmental conditions such as soil moisture, and competition from neighbouring plants.

Figure 5. *Chenopodium album* seedlings before flaming (left) and soon after flaming (right).

S-shaped logistic models, of the same type as those used in herbicide bioassay, can be used to describe plant response to flaming treatments in terms of fuel input in kg/ha (Ascard, 1994). When a mix of sensitive weed species in the 1 to 4 leaf stage were treated, propane doses of approximately 40 kg/ha (1840 MJ/ha) were needed to reduce weed numbers by 95%. Plants at 6 to 12 leaves required two to four times higher rates for control than those at the 1 to 4 leaf stage (Ascard, 1995a) (Fig. 6). The treatment dose therefore must be adjusted to weed species and their growth stage. The LPG rates given here are calculated for broadcast application. In practice, banded flame weeding in the crop rows is often used and the rates per hectare are then considerably reduced.

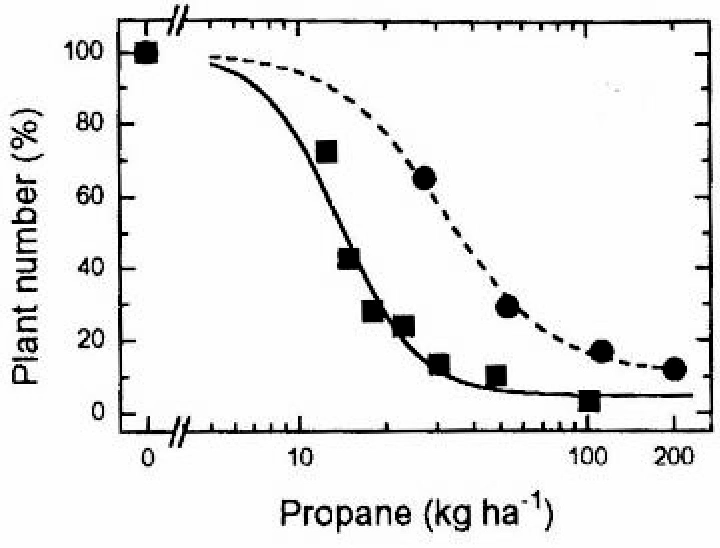

Figure 6. The effect of flame weeding on total annual weed number at early treatment (1 to 4 leaves) (■ □□ ■) and late treatment (6 to 12 leaves) (● – – – ●). Propane rates of 40 kg/ha killed 90% of the small weeds, whereas rates of 200 kg/ha killed less than 90% of the larger weeds (from Ascard, 1995a).

The susceptibility of plants to flaming depends on their ability to avoid heating and their heat tolerance. The extent to which flame heat penetrates crop and weed stands, and therefore the efficacy of flame weeding, depends on flaming technique, soil structure and leaf surface moisture. Tolerance to heat injury also depends on the protection offered by e.g. layers of hair and wax, lignification, and the species regrowth potential (Ascard, 1995a; Laguë et al., 2001; Leroux et al., 2001).

Weed species have different susceptibility to flaming (Ascard, 1995a). Sensitive species have unprotected growing points and thin leaves, e.g. *Chenopodium album*, *Stellaria media* and *Urtica urens*, and they can be killed at early seedling stages using propane doses of 20-50 kg/ha. At later stages (4 to 12 leaves), higher rates, 50 to 200 kg, are needed to kill these plants. Tolerant weed species with protected growing points, e.g. *Capsella bursa-pastoris* and *Chamomilla suaveolens*, allow the weed to regrow after flaming. While these weeds can be completely killed at early growth stages (<4 true leaf stage), repeated treatments are needed at later stages due to their ability to regrow.

Poa annua and several other grasses are very tolerant to flaming because of their creeping growth habit and protected growing points. Perennial weeds with large underground parts are also very tolerant to flaming. Repeated flamings are needed to control these weeds (Ascard, 1995a).

Recent research in Canada has shown that *Chenopodium album* and *Amaranthus retroflexus* susceptibility to flaming decreases as their development growth stages advances (Fig. 7). Annual grasses such as *Echinochloa crusgalli* and *Setaria pumila* are tolerant to flaming because their growing point remains underground or near the ground surface, and therefore protected, for a long period after their emergence (Sivesind et al., 2009). Onions and broccoli were moderately sensitive 10 to 15 days after transplantation but tolerant afterwards (Leblanc et al., 2007)

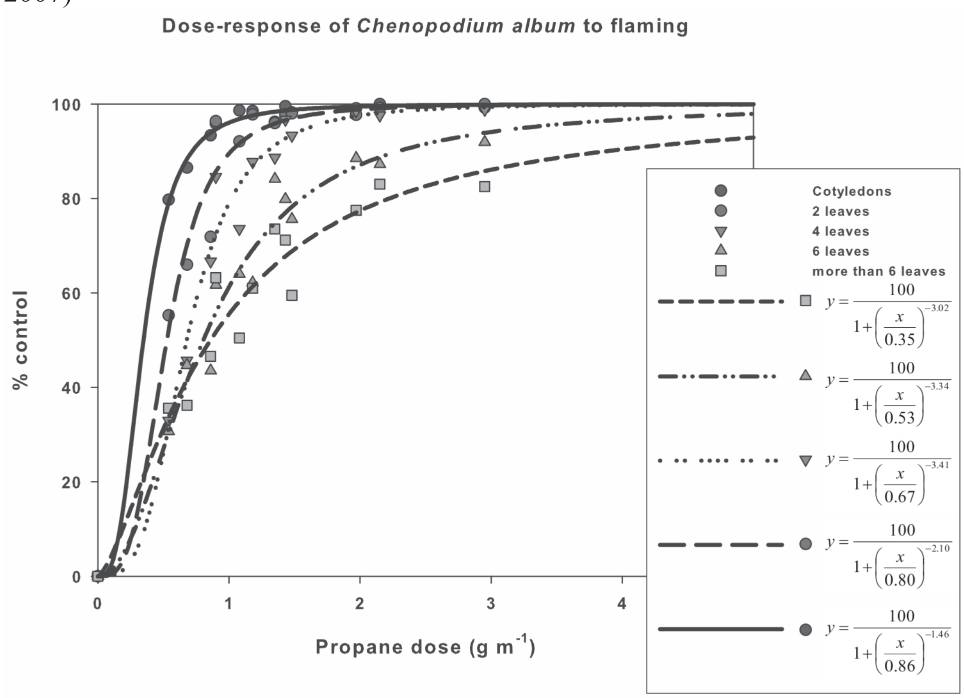

Figure 7. Dose response curves for flaming *Chenopodium album* in different growth stages. 1 g/m correspond to 57 kg/ha broadcast rate and 11 kg/ha banded rate at 90 cm row distance (from Leblanc et al. 2007).

Flaming technology

Flame weeders commonly use LPG (propane-butane mixture) as fuel. Propane flames generate air temperatures above 1000°C (Ascard, 1995b; 1998). Several types of burners and burner shields have been used for flaming (Kepner et al., 1978; Hoffmann, 1989). Burners must be set at an appropriate angle and height for optimum weed control.

Open burners, without cover, were used frequently in the US in the 1960s for selective flaming in the crop row and are still used for this purpose. Open burners are also used in small hand held flamers.

Flamers with an insulated cover over the burners are often used for non-selective weed control before crop emergence (Fig. 1), for weed control in urban areas, and for haulm destruction in potatoes. Covered burners for band flaming over the crop rows are also available. Flamers with covered burners are generally more effective than open flamers. Ascard (1995b) showed that an open flamer required 40% more fuel compared with a covered flamer to achieve good weed control.

The optimum travel speed of a flamer can be increased by increasing the number of burners, raising fuel pressure, and using larger nozzles (Ascard, 1995b; Laguë et al., 2001). European research has improved design of flame weeders in terms of heat transfer, energy efficiency and operating speed (Bertram, 1992, 1994; Storeheier, 1994; Ascard, 1995b). Improvements of the shielding of burners have made retention of heat close to the ground for longer periods possible.

A new machine for selective in-row flame weeding has been developed by the Danish company F Poulsen Aps Engineering, a weed robot (Patent No PCT/DK2005/000311). The system has a computer and a camera to detect the individual crop and weed plants in the row. Individual flame burners (plasma jets) adjacent to the crop plants are temporarily switched off whereas other jets in the array of multiple burners are kept on. The machine can operate at 4-5 km/h (F Poulsen Aps Engineering, www.visionweeding.com).

Effects of flaming on soil organisms

Soil is a very good insulator and can absorb a significant amount of heat with little increase in temperature (Reeder, 1971). In flame weeding, the thermal treatment is brief and only the uppermost few millimetres of the soil are heated. For example, Rahkonen et al. (1999) found that extreme LPG flame weeding raised soil temperature by 4^{o}C at 5 mm depth, and only 1.2^{o}C at 10 mm depth. Therefore, no significant damage to soil microflora or fauna is expected during a normal flame weed control operation. Rahkonen et al. (1999) found that although flame weeding using 100 kg/ha LPG led to a 19% reduction in soil microbial biomass at 0 to 5 mm depth, it had little effect at 5 to 10 mm depth. In a study of the effect of flame weeding on carabid beetles, a beneficial insect group, Dierauer and Pfiffner (1993) found no effect of flaming.

Costs and benefits of flaming

Flaming is an attractive weed control option because it leaves no chemical residue in the crop, soil and water, it can control herbicide tolerant or resistant weeds, and it can be used in crops where few or no herbicides are registered. In organic farming, flame weeding is a profitable method in carrots and several other vegetable crops to reduce the need for hand weeding. When flaming pre-emergence of the carrot crop is successful, the savings in labour for hand weeding is often in the range of 100 man hours per hectare (Rasmussen and Ascard, 1995).

In comparison with cultivation, flame weeding can be carried out on wet soils and does not bring buried weed seeds to the soil surface. Flame weeding usually provides better weed control than cultivation e.g. before crop emergence in small seeded crops.

The disadvantages of flame weeding include the high cost of labour, fuel, and equipment compared with herbicide application, low selectivity, and lack of residual weed control making repeated weed control treatments necessary. From a resource and environmental point of view, the high energy requirement and the release of carbon emissions could be seen as disadvantages. However, compared with other fossil fuels, propane combustion is relatively clean.

In North America, the cost of propane for two flamings are less than the costs of herbicides in maize, but flame weeding requires more time for application than do herbicides (Leroux et al., 2001). The total cost of flaming is often greater than that of chemical weed control, mainly due to high machinery costs and slow speed of field flaming (Nemming, 1994). When flaming is used in vegetable production such as carrots, labour costs for supplementary hand weeding might make up a large part of the total weed control costs as opposed to a strategy based on herbicides, where little or no hand weeding is required. However, in heat tolerant crops, such as maize, selective flame weeding is possible which eliminates the need for hand weeding.

Infrared radiation

Infrared (IR) radiators, driven by LPG, operate at red brightness temperatures of about 900°C with essentially no visible flame on the combustion surface. This type of true IR-radiator should not be confused with flame weeders using ordinary gas flame burners covered by an insulated shield, sometimes marketed as "infrared" weeders. This type of flame weeder is no different from the other types of covered flamers, which also work mainly by heat convection from the flames and to some extent indirectly by infrared radiation from the insulated cover, heated by the flames (Ascard, 1995b).

IR radiation was tested for thermal defoliation of cotton in the USA during the 1960s (Reifschneider and Nunn, 1965). It was used for weed control to some extent in Europe during the 1980s, but was replaced by flame weeders using covered flame burners. The use of IR radiators for weed control has not become popular because of their high equipment cost and low capacity compared with flame weeders (Ascard, 1998). Furthermore, IR radiators produce lower temperatures and therefore transfer less heat to plants compared with most flame burners (Parish, 1989).

Hot water

Hot water can be used where flaming is not desirable because of fire hazards. Hot water equipment has been introduced for weed control in urban areas (Rask and Krisoffersen, 2007) and in orchards (Kurfess and Kleisinger, 2000). Use of hot water however requires large amounts of water and energy, which makes the method less interesting on arable land.

Using hot water as a foliar spray, the energy used to obtain 90% reduction of *Sinapis alba* plant number in the 2-leaf stage was 3970 MJ/ha, corresponding to 110 kg/ha of diesel fuel, and a water use of approximately 10,000 l/ha. The plant stage at treatment was important as three times more energy was required when the seedlings were treated at the six-leaf stage compared with the two-leaf stage (Hansson and Ascard, 2002).

The energy use of hot water treatment is relatively high and attempts have therefore been done to improve application efficiency. By using a long insulated shield with nozzles or an insulating shield behind the nozzles, the control efficiency was improved and the effective travel speed could be increased to 8 km/h (Hansson and Ascard, 2002).

A hot water system from New Zealand uses hot foam to achieve an insulating effect and keep the hot water in contact with the weeds for a longer time. A biodegradable foam formulated from corn and coconut sugar extracts has been used to reduce heat dissipation during hot water application (Quarles, 2004). Addition of a surfactant to the water has been shown to allow higher travel speeds, up to 8 km/h, of hot water application equipment for effective weed control (Kurfess and Kleisinger, 2000).

Equipment with an optical system for patch spraying of hot water has been developed in The Netherlands by the company Front2Front (www.front2front.nl).

Steam

Steam has been extensively used for soil disinfection for over a century (e.g. Runia, 1983), but steam has so far not been widely used for weed control. The use of steam for weed control offers some advantages over hot water in that water use is considerably lower and steam may provide better leaf canopy penetration. Steam can be superheated to very high temperatures (400°C), to increase efficacy and shorten the required exposure time (Upadhyaya et al., 1993).

Steam equipment for use in urban areas has been developed in Denmark by WR Damp (www.wrdamp.dk). Three machines have been used regularly over a number of years (Rask and Kristoffersen, 2007).

Mobile soil steaming

Soil steaming has the potential for reducing laborious intra-row hand-weeding in row crop systems where herbicides are not used. Mobile soil steaming is commercially used on raised beds, especially in short-term field salad crops with a strong need to control soil-borne pathogens (Pinel et al., 1999). Steam is applied to the whole bed area and to a depth of 50 to 100 mm in the soil depending on the steaming time. Steaming causes high mortality of weed seeds, which could lead to effective and long-term weed control.

The current soil steaming technology has a very high consumption of energy, with diesel fuel use in the range of 3500 - 5000 l/ha. Moreover, it is very time-consuming, requiring 70 - 100 hours to treat one hectare. This has lead to the idea of band-steaming where only a limited soil volume is steamed, enough to control weed seedlings in the rows. The width of the treated intra-row band depends on how close to the crop plants inter-row cultivation is carried out. Steaming down to a soil depth of approximately 50 mm appears to be sufficient, because most weed seeds are small and will predominantly emerge from the top 20 mm of the soil profile.

Seedling emergence from natural seed banks was reduced by 99% when the maximum soil temperature reached 70^{o}C (Fig. 8) (Melander and Jørgensen, 2005). In field trials using a Danish prototype band steamer, an 80 to 90^{o}C soil temperature yielded 99% weed control, corresponding to 350-400 l/ha of diesel fuel when steaming a band 100 mm wide and 50 mm deep (Jørgensen and Melander, unpublished results). Commercial versions of band steaming equipment for weed control have recently been developed by the Danish company Yding smedie (www.ydingsmedie.dk).

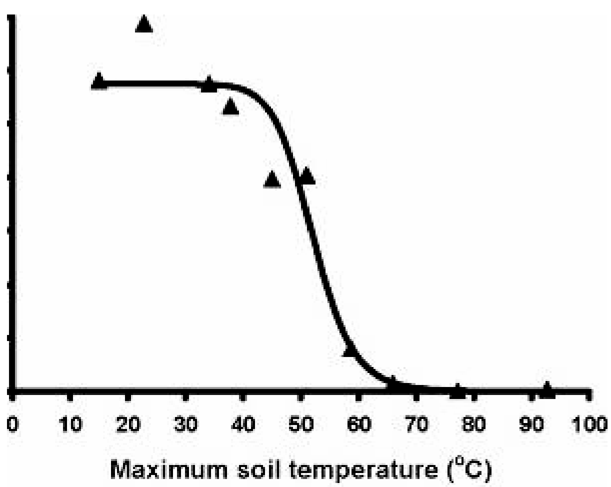

Figure 8. The relationship between maximum soil temperature obtained by steaming the soil at different time intervals and weed seedlings emergence from steamed soil (from Melander and Jørgensen, 2005).

Band steaming has been used commercially and evaluated in on-farm experiments in Sweden. A nine-row band steamer with a 700 kW diesel-driven steam generator treated 105 mm-wide bands, 50 mm deep, before sowing sugar beets and parsnips (Fig. 9). The travel speed was 0.25 km/h, resulting in a treatment time of 8 h/ha, and a water consumption of 8000 l/ha. Field experiments showed that a maximum temperature of 86°C in the middle of the steamed band at 40 mm depth was needed to obtain a 90% reduction of annual weed numbers, with a diesel use of 570 l/ha. At this rate, the labour requirement for hand weeding was 49 h/ha compared with 132 h/ha in the non-steamed plots. At a higher diesel use of 650 l/ha, the hand weeding time was reduced to 32 h/ha. The establishment of sugar beet plants was better in the steam treated rows than in the untreated rows (Hansson and Svensson, 2007).

Figure 9. Band steaming for weed control and partial soil sterilisation before sowing of sugar beets. This nine-row band steamer, built by a Swedish farmer, has a capacity of 1 ha per 8 hours and requires 690 l/ha of diesel fuel to obtain 95% reduction in weed emergence.

A major concern about steaming is its lethal effect on soil organisms other than weed seeds. While bacterial, fungal and enzyme activities were reduced significantly in response to steam treatment, soil water and nitrate contents, pH, water-soluble carbon and in situ respiration were not affected (Melander et al., 2004). The impact of these effects on crop performance was not investigated.

Hot air

Equipment with hot air for hard surface weed control has been developed by the Danish company Zacho Products (www.zacho.dk). The effect of hot air has proven to be comparable to other thermal methods, but the energy requirement was relatively high (Rask and Kristoffersen, 2007).

Electrical energy

Electrical energy has been used to kill weeds and sugar beet bolters (tall plants in the reproductive phase) (Diprose and Benson, 1984; Diprose et al., 1984; 1985; Vigneault and Benoit, 2001; Vigneault, 2002). The control equipment consists of a generator, a transformer, electrodes, and rolling coulters.

Two systems have been developed for weed control using electrical energy; the spark discharge method uses short-duration, high-voltage pulses with two electrodes around the plant, and the electrical continuous contact method use a high-voltage electrode touching the unwanted plant resulting in a current passing through the plant (Diprose and Benson, 1984). The technology requires weeds to be taller than the crop in a mixed weed-crop population to allow selective electrode contact with the weeds. Some damages are reported also on roots and rhizomes of weeds as the current flows through the plant into the root system before it dissipates into the soil. Plants with large below-ground parts are damaged to a lesser extent, and the root damage is greater in drier soils.

Field equipment for electrocution used in the past typically had a current of 6 - 25 kV and a power of 50 - 200 kW, and used diesel fuel. In experiments with Lasco EDS equipment at the North Dakota State University in the 1980s, an average travel speed of 5 km/h was used with a diesel use of about 8 l/ha, out of which 4 l/ha was used to generate electricity and the rest to run the tractor (Kaufmann and Schaffner, 1982).

Vigneault and Benoit (2001) calculated that the energy input for electrical weed control was between 418 and 16,500 MJ/ha for weed densities between 5 and 200 weeds/m^2, respectively. They concluded that electricity has advantages to control tall escaped weeds at low densities, but is not suitable as the primary method of weed control at densities of more than 200 weed stems per m^2 (Vigneault and Benoit, 2001).

While electrocution appears to be an interesting option in some situations, the commercial use is limited by several factors, including high equipment cost, inefficient control of small weeds, and a concern for the applicator safety.

Microwave radiation

Microwaves for dielectric heating have been investigated to kill weeds, seeds (Davis et al., 1971; Sartorato et al., 2006), and insects (Nelson, 1996; Pelletier and Colpitts, 2001). However, the effectiveness of microwaves in killing soil-borne seeds under field conditions is limited, because much energy is wasted in heating a large volume of soil to damage the seeds. Microwave radiation does not penetrate the soil deep enough due to its rapid attenuation, particularly in moist soils. Furthermore, the travel speed of the application equipment is extremely slow. The energy use of microwave-based weed control in a field test ranged from 10,000 to 34,000 MJ/ha, corresponding to diesel fuel consumptions of between 1000 and 3400 kg/ha (Sartorato et al., 2006). Microwave application equipment to control weeds has been designed but the inefficient results and the concern for applicator safety has limited its practical use.

Ultraviolet radiation

High levels of ultraviolet radiation (1 to 100 GJ/ha range) have been shown to control weeds (Andreasen et al., 1999). When plants are irradiated with UV, energy is absorbed by the plant tissue, giving similar damage to plants from e.g. flaming. Experimental equipment to apply high doses of UV has been developed by the Danish company Electro Light (www.optocleaner.com).

Laser

Lasers can be used to cut weed stems in row crops. When *Solanum nigrum* seedlings were cut below the meristems, about 10 J/mm of CO_2 laser energy was needed to obtain 95% reduction of the plant dry weight (Heisel et al., 2002). With a realistic power conversion ratio of 5%, the authors concluded that this corresponds to 2955 MJ/ha for a banded treatment of 10% of the surface of a sugar beet field with 250 plants/m^2. However, with current technology the lasers cannot be turned on and off quickly enough to allow for selective weed control in the crop row.

Freezing

Freezing with liquid nitrogen (-196^{o}C) and CO_2 snow (dry ice, -78^{o}C) have been compared with flaming for weed control. Freezing affected the weeds in a similar manner to flame weeding, but freezing required 6000 and 12,000 MJ/ha, for liquid nitrogen and CO_2 snow, respectively. Freezing, therefore consumed about three to six times more energy to obtain the same level of weed control as flame weeding (Fergedal, 1993).

Energy-use and environmental impacts of thermal weed control

An important advantage of using thermal weed control is the avoidance of the risk of chemical residues in soil, water and in the crop, associated with the use of herbicides. However, many thermal methods require much fossil fuel, and their value in sustainable farming systems has been debated.

While caution should be exercised in comparing the energy use efficiencies of thermal methods using data from different studies with different kinds of fuels and energy conversion factors, some rough comparisons can be made.

Thermal methods described here generally use more energy compared with mechanical and chemical weed control. For example, in potato production a broadcast application of flaming required about ten times more energy than mechanical or chemical weed control (Fykse, 1985) or haulm killing (Jolliet, 1993, 1994). These data take into account the energy needed for herbicide synthesis and application, but not the energy required to eliminate herbicide residues from the water, soil and atmosphere.

For flame weeding, the energy use was based on a broadcast application using 50 kg/ha of propane, which together with the energy for transport and processing of propane, as well as the diesel used for application, will be about 2700 MJ/ha (Jolliet, 1993). However, in practice flaming is often applied in bands in the crop row, which reduces the energy use to a fraction of this value.

Weed control using IR radiation requires roughly similar amounts of energy compared with flame weeding, (Ascard, 1998), whereas hot water treatment used about twice as much energy (Hansson and Ascard, 2002) compared with flame weeding for equivalent weed control. The energy input for electrical weed control can be higher or lower than flame weeding, depending on the weed density (Vigneault and Benoit, 2001). Microwave weed control used about 40 times more energy than flame weeding (Sartorato et al., 2006), and UV radiation used about four times as much energy (Andreasen et al., 1999) compared with flame weeding for equivalent weed control. Freezing used three to six times the energy compared with flaming for equivalent weed control (Fergedal, 1993).

Several of the energy requirements listed above were obtained from using prototype equipment and improvement in their energy use efficiencies is possible. Moreover, all of the above energy figures are calculated for broadcast treatments, for comparison reasons, but in practice several of these methods can be justified as banded application only to reduce energy input and costs. For example, conventional broadcast soil steaming for deep soil sterilization uses about 50 times more fuel, but the newer shallow band steaming (Melander and Jørgensen, 2005; Hansson and Svensson, 2007) uses five to ten times more fuel than flame weeding, for equivalent weed control. Moreover, soil steaming will result in a longer-lasting reduction of seedling emergence compared with flaming.

Although flaming requires approximately ten times more energy input at the farm gate level than chemical or mechanical control, the energy inputs of weed control methods should be considered in relation to other farm inputs. The energy use for weed control is often a minor part of the total energy use and environmental impact of crop and production (Foster et al., 2006).

The environmental impacts of thermal control with flaming and chemical control with herbicides in agriculture on soil, water, air and energy resources has been studied in Canada. The study showed that thermal control methods have environmental benefits in terms of impacts on soil and water, but environmental costs in terms of air quality and energy use (Laguë et al., 2001). A similar study compared different combinations of chemical, mechanical and thermal methods for potato plant top- killing. They concluded that mechanical top-killing presented the least negative overall environmental impact on air and soil, while chemical top-killing had the most, and the thermal method was intermediate in impact (Jolliet, 1993, 1994).

Many factors have to be considered in the evaluation of weed control and farming methods. Pollution from chemical pesticides and the related health hazards and environmental costs have to be weighed against other types of air pollution, and the use of natural resources. The result of any environmental impact assessment or life cycle analysis, such as those mentioned above, will depend on the methods used for weighting and comparing different environmental impacts.

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Tools and innovations in mechanical weed control in north-western Europe

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Weed control is one of the main problems in organic farming in Europe. Labour for hand weeding is expensive, especially in slow-growing and low-competitive vegetable crops and difficult to organise. This paper provides an overview of recent developments, mainly aimed at increasing capacity and accuracy, in mechanical inter-row and intra-row weed control in row crops in north-western Europe. Steering systems developed to improve the accuracy of mechanical inter-row weed control cultivators have enabled the width of the untreated strip to be reduced considerably without loss of driving speed. The challenges of intra-row mechanical weed control are to increase capacity and efficacy close to crop plants and to improve the economics of intelligent intra-row weeders. Research and practice concerning intra-row weed control have successively focused on the use of harrowing, brush weeding, torsion weeding and finger weeding. One example of recently developed tools use compressed air to control the weeds within crop rows. There are also high-precision cultivators that moves in and out of the row. Improvements have been made in the detection of crop and weed plants, fast actuation in crop rows and robotics. The involvement of larger manufacturers could boost these technologies and thereby helps to meet steadily increasing demand for more effective weed control tools.

Introduction

The awareness of government, consumers and farmers of possible adverse side-effects of chemicals has increased over recent decades and has resulted in regulations on human health aspects. One example is the legislation on herbicide concentrations in drinking water, with the limit set at 0.1 μg/L. In the Netherlands, 80% of the pesticides contaminating raw drinking water were herbicides (Lotz et al., 2002).

Concern has risen not only with regard to human health, but also with regard to side-effects of herbicides on biodiversity through their effect on plant species composition, diversity, development, growth or morphology. Plants are an important part of the habitat in relation to other organisms such as birds and insects, providing them with food, shelter and an environment in which to reproduce (Freemark and Boutin 1995; Moreby and Southway 1999).

These regulations, together with a significant decrease in the number of new herbicides entering the market, are strongly reducing the number of weed control options available to farmers. At present, the number of herbicides available for minor crops is already insufficient. In future, this problem is expected to extend to the major crops as well, not only due to stricter regulations but also to development of herbicide resistance in weeds (Menchari et al. 2006; Marshall and Moss 2007; Rubin et al. 2007; Kropff et al. 2008).

During the last decades, the interest in organic farming systems has increased. One of the main problems in organic farming is weed control especially in slow-growing and non-competitive vegetable crops (van der Weide et al. 2008). Labour for hand weeding is expensive (Riemens et al. 2007) and usually not easily available in north-western Europe. Examples of manual hand weeding in northern European countries ranges from 46 h ha^{-1} in planted vegetables to 177 h ha^{-1} in direct-sown onion (*Allium cepa* L.) (van der Weide et al. 2008) in the Netherlands, and 100- 300 h ha^{-1} in onions and carrots (*Daucus carotus* L.) in Denmark and Sweden (Sorensen et al. 2005).

Vegetable crops with poor competitive ability, such as carrots and onions need to be kept weed-free during the so called critical period in the early growth stages to avoid yield losses (van Heemst, 1985). Even low initial weed densities can result in almost total yield losses (Laber & Stützel, 2003). Therefore, careful weed control is needed, and a strong reduction in the amount of manual labour is essential for the future expansion of organic production of vegetables. This paper provides an overview of recent developments in mechanical inter-row and intra-row weed control in row crops in north-western Europe.

Developments in sensing and actuation in tools for mechanical weed control

Inter-row weeding

In recent decades, developments concerning inter-row weeding have mainly been aimed at increasing accuracy without losing capacity. To improve the accuracy of mechanical weed control cultivators, several steering systems have been developed. These systems can be discriminated by their mode of crop row detection:

- Detection of the crop row with the human eye only;
- A guidance wheel on the row crop cultivator following a furrow between two rows;
- Sensing of the crop row mechanically with gliders that prevent the hoe running over the crop row (see Fig. 1);
- Detection of the crop row or crop plants with camera-based optical steering systems (e.g. www.eco-dan.dk and www.fp-engin.dk);
- Detection of the crop row and steering of the implement using satellite navigation (RTK-DGPS) placed on both the tractor and the cultivator.

Figure 1. Crop-steered hoes with sliders in beans (*Phaseolus vulgaris* L.) (photo by Pieter Bleeker).

With accurate guidance the width of the untreated strip in the crop row can be reduced considerably without yield loss, for example untreated strips of 5 cm have been reported in single line row (Ascard and Mattson 1994; Melander and Hartvig 1997). Moreover cultivator-mounted RTK-GPS in the Netherlands resulted in untreated strips of 3 cm with a driving speed of 4 km h^{-1}.

The most common methods for inter-row weeding were illustrated and described by Bowman (1997), Cloutier et al. (2007b) and Van der Schans et al. (2006) and are not discussed further here.

Intra-row weeding

The main problem for intra-row weeding is discriminating between crop and weed plants, and the ability of the tools to get close enough to the crop plant. Most weeders are non-selective, which is not a problem when crop plants have a head start in development and a larger size than the weed plants at the moment of control. However, when the difference between crop and weed plants is smaller, not all weeds can be mechanically controlled if significant crop yield reductions are to be avoided. As a result, the improvement of accuracy and capacity, but also of sensing the crop and weed plants are both important aspects in the development of mechanical intra-row weeders.

The development of sensing techniques to date has been as follows:

- Recognition of weed plants in the crop row with the human eye and subsequent removal with hand-held hoes or even just by hand (= Simply ordinary hand weeding, Fig. 2);
- Removal of weed plants based on differences in anchorage and strength of crop and weed plants. Crop plants stay rooted and the smaller and more easily uprooted weeds are physically removed, e.g. with finger weeders (Fig. 3); or compressed air.
- Actual mechanical sensing of crop plants with tines connected to hydraulic devices that allow the rotary cultivator/tool to move in and out of the crop row (Fig. 4);
- Optical sensing of the crop plants with simple light beam sensors (Fig. 5) or with more sophisticated cameras that recognise the shape of crop plants, linked with actuators moving in and out of the crop row (www.visionweeding.com; Dedousis et al. 2007).
- Creation of an electronic field map with geo-referenced seed positions for each individual crop seed using Real Time Kinematic DGPS technology. The map is used for coarse localisation of crop plants and should be combined with more precise guidance systems to achieve accurate and reliable intra-row weed control (Griepentrog et al. 2005).

In the past decades, research and practice have focused in turn on the development and improvement of the use of harrowing, brush weeding, torsion weeding and finger weeding (van der Weide et al. 2008). At present, the capacity of finger and torsion weeders is still relatively small (4-10 km h^{-1} and 3-4,5 m width). Harrowing is already possible with a much higher capacity, up to 12 km h^{-1} and 24 m width; but in practice a driving speed of 8 km h^{-1} and a width of 6 m are most commonly used. Larger weeds can already be hoed automatically in planted crops, but the driving speed is still rather low (3 km h^{-1}) and a few cm of soil around the crop plant still remains untreated.

More recently developed tools make use of compressed air to control the weeds in the crop row (trade name Pneumat weeder, Lütkemeyer 2000). A commercially available weeder (SARL Radis) combines crop sensing with automatic movement of the actuator in and out of the row (Van der Schans et al. 2006) and makes use of a light beam directed over the crop row, perpendicular to the driving direction. Whenever this light beam is interrupted, a crop plant is detected and based on the interruptions, a hoe is moved in and out of the crop row. The driving speed is slow and the number of crops in which the machine can be applied are still limited.

Pictures and more information on harrows, brush weeders, torsion weeders and finger weeders and recently developed cultivators and tools for mechanical intra-row weed control can be found on the website of the Physical and Cultural Weed Control Working Group of the European Weed Research Society (www.ewrs.org/pwc) and in publications by Van der Schans et al. (2006), Cloutier et al. (2007b) and van der Weide et al. (2008).

With appropriate machine adjustments, the above described developments have made intra-row control of small weeds possible in many crops and in several growth stages (Van der Schans et al. 2006). In slow germinating, small seeded and low-competitive crops like carrots, direct-sown leeks and onions, intra-row weeding remains difficult. For example direct sown onions have a very low competitive ability and the presence of weeds in an early growth stage can cause significant yield losses. Direct-sown onions are very sensitive to mechanical damage soon after emergence, which makes distinguishing between crop and weed plants very important. At present, the sensors of commercially available weeders are not yet capable of recognising very small direct-sown onions. However, the amount of hand labour can be reduced by 40 and 70 % in direct-sown onions and transplanted onions respectively by using the torsion or finger weeder (Ascard and Fogelberg 2008; van der Weide et al. 2008). The sensors and software are currently being modified to improve the possibilities for intra-row cultivation in onions (limited to single line rows and onions seeded or planted in clusters).

Figure 2. Manual removal from rows of onion (*Allium cepa* L.) of weeds that escaped mechanical weeding (photo by Johan Ascard).

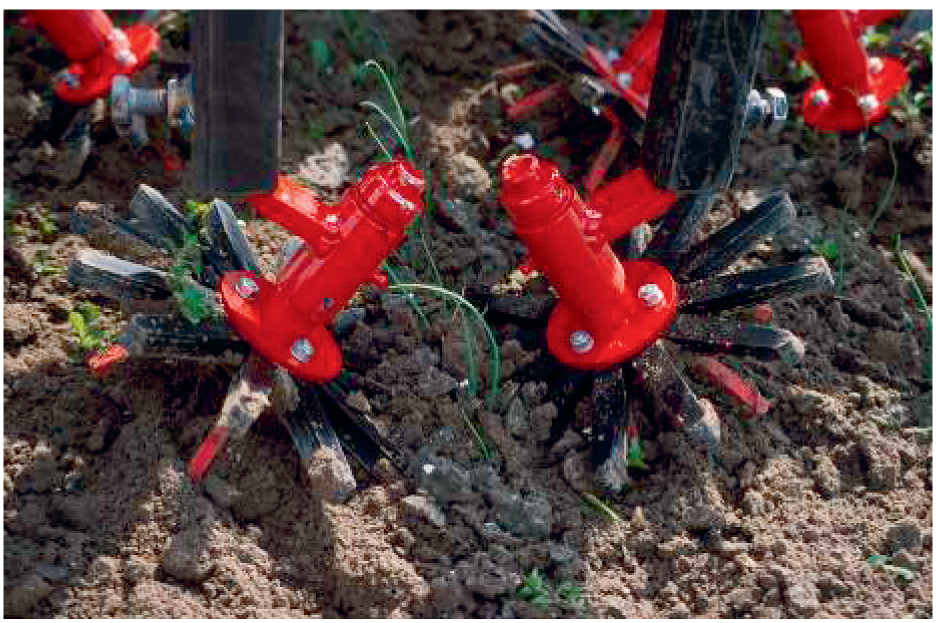

Figure 3. European style finger weeders in onions (*Allium cepa* L.) (photo by Pieter Bleeker).

Figure 4. Mechanical sensing of tree trunks in fruit orchard with a tine connected to a hydraulic device allowing the rotating tool to move in and out of the tree row (photo by Johan Ascard)

Figure 5. Advanced weeder (SARL Radis) that senses crop plants and subsequently cultivates in the crop row (photo by Pieter Bleeker).

Use of mechanical weed control tools in north-western Europe

In organic farming, hoes and harrows are available and applied on most reasonably sized organic farms (min 10 ha). Finger weeders and torsion weeders are also quite common. Several manufacturers have produced finger weeders, which have consequently replaced brush weeders in many places. Few pneumatic and advanced intra-row hoes have so far been sold in north-western Europe (about 25 per year).

Mechanical weed control in conventional arable cropping systems in north-western Europe is less common. Harrows are mainly used before crop emergence, for example in silage maize. Row crop cultivators are commonly used for inter-row weeding in several horticultural crops, especially where no effective herbicides are available. Ridging is common in potato and some vegetables.

Challenges for mechanical weed control

At present, mechanical weed control systems can be just as profitable as systems with herbicides (Mohler 2001; Peruzzi et al. 2005) depending on the scale at which the comparison is made; large (national) or small (farm) level. At the farm level, weed control has to add value to the crop, so mechanical weed control has to be as profitable as herbicide control (Cloutier et al. 2007b). When the comparison is made at the national level and the costs of removing herbicides or their metabolites from surface water and other environmental compartments are included, the use of herbicides is probably uneconomical compared with mechanical weed control. However, the reality is that the economic feasibility of technologies is determined at the farm level.

A higher level of precision in space and time in the sensing of crop and weed plants and a higher capacity and efficacy close to crop plants is needed to improve the economics of intelligent intra-row weeders compared with herbicides at the farm level. Several research groups are working on improving these aspects (Gerhards and Christensen 2003; Van Evert et al. 2006; Hague et al. 2006). In general, sensing systems are already fast enough to detect plants at driving speeds of 10 km h^{-1}. Most weed removal systems have mechanical limitations at this speed. As a result, the capacity of systems combining sensing equipment with non-selective actuators is usually low, which makes the systems time-consuming to operate (van der Weide et al. 2008). One of the possible solutions is robotisation. In the Netherlands, Van Evert et al. (2006) have developed a robot that is able to move autonomously and to detect 89 to 99% of volunteer potato plants in commercial maize fields based on a combination of size, shape and colour of green elements in an image. Developing this kind of prototype into commercially available weed control applications that are user-friendly, reliable and cost-effective is one of the challenges of robotics in weed control.

The involvement of larger manufacturers could further boost the development and commercialisation of these technologies. At the same time, new developments in arable farming such as the introduction of crops for biofuel might help to increase farmers' income and thus their capacity to invest in new technologies.

Perhaps one of the biggest challenges mechanical weed control is facing today is to increase machine workability under different weather and soil conditions. The outcome of mechanical weed control is known to depend heavily on soil conditions (Kurstjens and Kropff 2001) and weather conditions can impede the required mechanical weed control (Kempenaar et al. 2005). In addition, tractors are generally required to operate mechanical weeders and for this too, weather conditions must be favourable and the soil must be dry. The development of lighter equipment could improve the workability.

Currently, advanced technologies such as sensing crop and weed plants and robotics are regarded as an important way to improve mechanical weed control in existing cropping systems. However, the adjustment of cropping systems to new developments and technologies may be equally important. One of those developments is societal pressure to reduce the energy consumption of plant production, which may lead to reduced ploughing and no-till systems (Kropff et al. 2008). The disadvantages of those systems are the higher weed densities, and sometimes less workable soil structure, and therefore the higher demand for weed control. Despite these disadvantages, two types of no or reduced tillage cropping systems using mechanical weed control have been developed and are being applied in practice in North America (Cloutier et al. 2007a). The adaptation of these non-chemical non-inversion systems to suit northern European conditions will demand a change in cropping systems, together with further investment in specialized tools adapted for mechanical weed control in ploughless systems.

Another example is the development in onion cropping. Onions are normally sown in such a way that the space between individual onion plants is uniformly distributed and narrow. Nowadays, it is possible to establish plants in clusters with abundant space between the clusters, which makes intra-row weeding possible, without yield loss (Bleeker et al. 2007). Another promising option under investigation is the use of clean (free of weed seeds) compost strips under which onions are sown (unpublished data Applied Plant Research, 2007). The preliminary results show that a layer of 2 cm is enough to prevent weed emergence, but not enough to reduce onion emergence. With this method, onions will experience less competition from weeds in the row, which will reduce the need for intra-row weeding.

Conclusions

Due to the development of steering systems, the accuracy of mechanical weed control cultivators has improved markedly. The width of the untreated strip after inter-row weeding can nowadays be reduced considerably without loss of driving speed. The research focus on accuracy and capacity in intra-row weeding has led to the development and improvement of harrows, brush weeders, finger weeders and torsion weeders. As a result, intra-row weeding is now possible in many crops and manual weeding can be reduced considerably. Mechanical control of larger weeds within rows and mechanical weed control in sensitive row crops such as onions, remains a problem at present. Sensing technologies combined with non-selective actuators may help solve this problem in future. One of the bottlenecks in this combination of technologies is caused by the mechanical limitations of actuators moving in and out of the row, which results in low driving speeds and thereby low capacity. The development of autonomous robots that can sense and remove weed plants within the row may provide the solution for mechanical weed control in sensitive row crops. In case of multiple line rows or hardly competitive crops with a regular dense density in the row (carrots) other solutions are needed.

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Precision agriculture and weed control in horticulture

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Precision agriculture is a technique that could be adopted to reduce herbicide inputs or increase the precision of tillage operations. Precision agriculture generates and uses spatially referenced data. For weed management, it offers new opportunities for a "see-and-kill" approach or site-specific weed management (SSWM). The precision agriculture community can contribute to the "see" part while the selection of proper action threshold and weed control approaches remains in the hand of weed scientists/technologists working with engineers. By limiting the field area where treatments are required, SSWM can transform techniques that are not suitable for whole field application to practical and economical solutions. For example, weed control with electric pulses is not competitive for full field coverage (Vigneault and Benoît 2001). However, it might find an application when individual weeds can be identified and localized to guide a robotic arm equipped with a high voltage electrode as was studied during the Patchwork research program (Rabatel 2004).

On economic grounds, SSWM is difficult to justify for cereal and oilseed crops (Maxwell and Luschei 2005). For other crops or in biological production systems, the economic incentive may be better (Sørensen et al. 2005; Leblanc and Cloutier 2006). Protection of the environment may benefit from SSWM but unless regulations limiting the use of herbicides are enforced, adoption rate of SSWM for the sole purpose of environmental protection should be expected to be low. The value of SSWM can be increased when it is implemented as a tool to build field-specific databases that could be used to make better decision for SSWM as time progresses (Maxwell and Luschei 2005). With GPS, it is possible to implement various weed control approaches (different techniques and/or at different intensities) in small sub-field areas and to acquire spatially referenced data on weed populations and crop yield. With this data, models can be constructed on a field by field basis. For example, after gathering data for a number of years, models relating yield loss to weed infestation on a yearly basis or models relating weed infestation in subsequent years as a function of infestation in the current year can be developed and used for developing more efficient weed control strategies.

Seeing weeds can be achieved either in near real-time when weed control is being performed or before treatment. Implementation of precision weed control should be based on two interrelated components: weed spatial distribution and weed detection. The main issue regarding spatial distribution is the scale that should or can be considered. But scale is also an issue when considering weed detection.

Technologies to detect large and dense weed patches are not suitable for the detection of individual weed seedlings.

Spatial scale

It is convenient to split the spatial scale in three: one meter and above; a few centimeters and sub-centimeter scales or meter, centimeter and sub-centimeter scales in short. The larger scale is useful to identify and localize fairly large weed patches in a field. Mapping these patches can reveal where weed control is required and where it is not. This information can be used to plan weeding activities more efficiently by avoiding traveling to field areas where weed control is not required or can be delayed. Working with weed patches, the concept of a weed patch has to be defined and this raises some issues as multi versus single species patches and minimum weed density in relation to crop tolerance. Working with patches also calls for a mapping approach as patches can only be delineated after acquiring data over the full area. Mapping at the half-meter scale and above is routinely achieved using current real time GPS technologies (WAAS and alike) (Stafford 2000). While the mapping approach has been studied a number of times for cereal and oilseed crops (Brown and Noble 2005), a search of bibliographic databases (CAB, Agricola, Current Contents for years 2000-07) failed to identify scientific literature on the use of weed mapping in horticulture.

Conceptually, the weed patches approach can be applied down to the centimeter scale but this is probably excessive. This scale is more appropriate for precisely defining rows of plants or individual crop plant along the row for some crops. As more precision is obtained, weeding can be performed closer to the crop plants. Locating plants and rows can be achieved using maps or in real time using appropriate sensors. Weeding can be performed by mechanical or thermal methods or by using small doses of herbicides applied to individual weeds (Slaughter 2000). In horticulture, most of the research and development efforts on precision weeding were based on precisely defining row and crop plant locations.

At the centimeter/sub-centimeter scale, individual seedlings can be identified and this opens the door to the concept of “single plant husbandry”. This can be achieved in two ways: (1) registering the position of each seed or transplant in a database (Ehsani et al. 2004). Later when a plant is detected, its position can be compared with the positions recorded in the database. In case of a match, the plant is automatically recognized as crop (Vinstrup et al. 2005); (2) detection and identification of each plant based on some fingerprint such as reflectance (Hahn and Muir 1994) or fluorescence characteristics (Panneton et al. 2006).

Weed detection

Weed detection and identification within a crop has been an active area of research over the last two decades. In general, four approaches can be defined: (1) airborne remote sensing; (2) ground-based remote sensing; (3) contact sensing and (4) crop mapping. Weed detection can proceed by positive detection where a plant is detected and identified as a weed or by negative detection where any plant that is not a crop plant is a weed. With positive detection, it may be possible to identify weeds to the species level while this is not feasible using negative detection. In the case of negative detection, crop layout can provide useful information (*e.g.* rows, spacing on the row) (Onyango and Marchant 2003).

Airborne remote sensing

Airborne remote sensing (ARS) can cover a wide range of spatial scales from a few meters with satellite imagery down to the centimeter scale with aerial photography. Both imagery in the visible and the infrared (IR) range of the spectrum has been used. ARS technologies are better suited to find well-defined large weed patches. Detection and identification of sparsely distributed weed seedlings in crop fields should be based on dense spatial information that cannot be provided by ARS (Brown and Noble 2005). Other limitations associated with ARS are weather conditions (clouds, atmospheric distortion) and availability of the image when it is needed although this last limitation tends to be relaxed as more satellites become available (Shaw 2005). One interesting potential application of ARS to SSWM is the use of imagery obtained after harvest to identify patches of difficult-to-control perennial weeds as previously developed for cotton (Shaw 2005).

Ground-based remote sensing

Ground-based remote sensing (GRS) uses technologies that are similar to ARS. However, there are several advantages in terms of data collection: almost independent from weather conditions, fine spatial resolution in the sub-centimetre range, more flexibility in the selection of spectral content of the image and better control for timing the data acquisition with crop/weed status. Further, GRS opens the door for multi-resolution systems, multiple viewpoints and controlled lighting (Brown and Noble 2005).

GRS technologies can be based on imaging or on point sensors. GRS imaging sensors give access to fine resolution data offering two advantages over ARS: (1) the possibility to analyse the shape of the object in the image (shape of individual plant or leaf) and (2) minimum spectral mixing at the pixel level (*i.e.* when an image pixel contains spectral information from various objects such as soil and plants or soil and crop and weeds). Such detailed data can be used for plant species identification based on spectral content (Mao et al. 2005) or leaf shape (Neto et al. 2006) for example. Point sensing technologies can use spectral information (Hahn and Muir 1994) or fluorescence (Keränen et al. 2003; Panneton et al. 2006) as a fingerprint to identify the object in the field of view of the sensor. Point sensing technologies are better suited for real-time application where the sensing, detection and decision processes occur in the field at the time of application. Locating the point sensor at a known location with respect to the weed control apparatus provides the required spatial reference. Both imaging and point-sensing GRS can be combined on a single platform. For example, a robotic weeder can obtain image data that is used to locate individual or connected group of plants and use this information to guide a point sensor to obtain more detailed spectral or fluorescence data to perform plant species identification.

Contact sensing

Contact sensing is used to precisely locate the position of a crop row and is normally used in conjunction with mechanical weeding (Leblanc and Cloutier 2006). Contact can be made with a guiding furrow or the sides of a ridge. In these cases, the implement blindly follows the furrow or the ridge. A lightweight sensing arm coupled to an electrical control system can hydraulically adjust the position of the implement with respect to the row by sensing the base of the crop plants. The sensing arm can also be replaced by an optical look-ahead system that locates the crop row as with the Eco-Dan™ technology (Eco-Dan A/S, Denmark).

Research Focus to Address the Needs of the Future

- The use of plant reflectance and images for weed/crop discrimination has been well researched. Spectral characteristics of crop and weed species are very similar. This explains the relatively little success of research to develop weed detection systems based on reflectance alone (Stafford 2000). Image analysis may have potential but currently this approach is at best difficult (Manh et al. 2001) and requires high spatial resolution images (mm range) and large computing power. In low infestation areas where most of the plants are not overlapping, weed recognition by image analysis is certainly feasible but when infestation level is higher and leaves from neighboring plants overlap, feasibility is questionable from a practical point of view. UV-induced fluorescence was shown to have potential for plant fingerprinting and weed/crop discrimination (Keränen et al. 2003; Panneton et al. 2006). If this potential is confirmed, it could be used alone or in conjunction with reflectance and/or imaging technologies to increase discriminating potential.
- As mentioned earlier, there is a lack of research on mapping approach applied to weeds in horticulture. The main reason is probably that technologies working at a finer scale seem to be better adapted to horticulture as crop value is often high and acreage smaller. Also, for a number of horticultural crops early in the growing season, crop plants are isolated one from the other and are laid out following a well defined pattern that could be used as *a priori* knowledge to help in weed/crop discrimination.

- Another issue is the lack of generality in several precision horticulture technologies. For example, using color images, fairly accurate weed classification can be achieved for cauliflower/weeds system (Onyango and Marchant 2003). These results cannot be generalized to another crop having different reflectance characteristics, planting layout and plant geometry. While the method may be applicable to other similar cases, it will require extensive calibration before it can be implemented on a wider scale. Variations in weed phenotype associated with geographical location and variations in crop phenotype associated with varieties add to the challenge.
- In the end, fusion of data about crop location (even approximate), image, reflectance and fluorescence data will offer the best chance of success. This fusion of technologies is becoming a realistic alternative as optical technology, led by demands outside of agriculture, is developing at an increasing rate. As a result, monitoring and control ability should increase substantially over the coming years with an associated reduction in cost (Miller 2003).
- In the context of precision weed management, proper definition of an action threshold is a challenge. As data at a finer scale is available, models suitable at the field scale must be revisited and adapted to smaller scales (Shaw 2005).

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