8 Mechanical Weed Management

D.C. Cloutier,[1] R.Y. van der Weide,[2] A. Peruzzi[3] and M.L. Leblanc[4]

[1]*Institut de Malherbologie, 102 Brentwood Rd, Beaconsfield, Québec, QC, Canada, H9W 4M3*; [2]*Applied Plant Research, PO Box 430, 8200 AK Lelystad, The Netherlands*; [3]*Sezione Meccanica Agraria e Meccanizzazione Agricola (MAMA), DAGA – University of Pisa, via S. Michele degli Scalzi, 2 – 56124, Pisa, Italy*; [4]*Institut de Recherche et de Développement en Agroenvironnement, 3300, rue Sicotte, C.P. 480, Saint-Hyacinthe, Québec, QC, Canada, J2S 7B8*

8.1 Introduction

Weed control has always been closely associated with farming. It is very likely that the first weeding action was by hand-pulling. This was followed by using a stick which became a hand-hoe. As agriculture became more mechanized, fields were successfully kept weed-free with mechanical weed management techniques and tools pulled first by animals and eventually by tractors (Wicks *et al*., 1995). The appearance of herbicides in the mid-20th century contributed to a decreased reliance on mechanical weeders on farms. Nevertheless, these implements have continued to evolve and are very efficient and versatile in controlling weeds in a variety of cropping systems.

Mechanical weed management consists of three main techniques: the use of tillage, cutting weeds and pulling weeds. These three techniques are presented separately in this chapter.

8.2 Tillage

According to the American Society of Agricultural Engineers (ASAE, 2005), tillage generally refers to the changing of soil conditions for the enhancement of crop production. It can be further subdivided into three categories: primary tillage, secondary tillage and cultivating tillage (Wicks *et al*., 1995; ASAE, 2004). This section is further subdivided into two subsections: with or without soil inversion.

Cropping systems with soil inversion

Primary tillage

Primary tillage is the first soil-working operation in soil-inversion-based cropping systems. Its objective is to prepare the soil for planting by reducing soil strength, covering plant material, and by rearranging aggregates (ASAE, 2005). In these cropping systems, primary tillage techniques are always aggressive and usually carried out at considerable depth, leaving an uneven soil surface. In other cases, primary tillage may leave a more even soil surface, e.g. when soil packers are used in association with ploughs. For weed species that are propagated by seeds, primary tillage can contribute to control by burying a portion of the seeds at depths from which they are unable to emerge (Kouwenhoven, 2000). Primary tillage can also play a role in controlling perennial weeds by burying some of their propagules deep, thereby preventing or slowing down their emergence. Some of the propagules can be brought up to the soil surface, where they will be exposed directly to cold or warm temperatures or desiccation conditions (Cloutier and Leblanc, 2001; Mohler, 2001). The tools used to perform

 Non-chemical Weed Management (eds M.K. Upadhyaya and R.E. Blackshaw)

primary tillage in soil-inversion-based cropping systems are mainly mouldboard ploughs, but disc ploughs, powered rotary ploughs, diggers and chisel ploughs can also be used for this purpose (Barthelemy *et al.*, 1987; Peruzzi and Sartori, 1997; Cloutier and Leblanc, 2001; ASAE, 2005).

Secondary tillage

In secondary tillage, the soil is not worked as aggressively or as deeply as in primary tillage. The purpose of secondary tillage is to further pulverize the soil, mix various materials such as fertilizer, lime, manure and pesticides into the soil, level and firm the soil, close air pockets, and control weeds (ASAE, 2004). Seedbed preparation is the final secondary tillage operation except when used in the stale or false seedbed technique (Leblanc and Cloutier, 1996). The equipment used to perform secondary tillage are different types of cultivators, harrows (disc, spring tine, radial blade and rolling) and power take-off (PTO)-powered machines. Several of these implements may also be used instead of common primary tillage implements (ploughing, digging, etc) to prepare fields. In these cases, the soil is tilled (crumbled and stirred) down to a depth of 10–15 cm, which is beneficial in conserving or increasing soil organic matter content, and in saving time, fuel and money (Barthelemy *et al.*, 1987; Peruzzi and Sartori, 1997). Initially there might be some problems with weeds when using reduced-tillage techniques, since they are not effective against the potential flora and they might even stimulate weed seed germination. Consequently, mechanical weed management has to be intensive and performed with particular care using secondary tillage, seedbed preparation and the false seedbed technique. Optimally, farmers will alternate ploughing with chiselling and use reduced tillage to optimize soil management, till it at different depths, and change the mechanical actions year after year in order to conserve organic matter and to increase fertility, to save time, fuel and money and, last but not least, to improve annual and perennial weed species control and crop development and yield (Peruzzi and Sartori, 1997; Mohler, 2001; Bàrberi, 2002).

In the following subsections, seedbed preparation is presented first, followed by some noteworthy techniques such as tilling in the dark, using the false or stale seedbed technique, and raised bed cultivation.

SEEDBED PREPARATION. The cultivators are always equipped with rigid or flexible tines working at a depth (on ploughed soil) ranging from 15–25 cm when heavy cultivators are used with the aim of reducing clod size, lifting the soil, increasing soil roughness and controlling perennial weeds, down to 5–10 cm when light cultivators are used to prepare the seedbed. The tines may be rigid or flexible. The rigid tines are often partly or completely curved, work at greater depths, reduce clod size, have a good weeding action on actual weed flora by uprooting them, and may also partly control the vegetative and reproductive structures of perennial species that are brought to the soil surface where they may be exposed to the elements. The flexible tines are usually curved, work at a shallow depth, require a lower drawbar pull, and crumble and intensively stir the tilled soil layer. The tines vibrate with the forward movement of the tractor, which helps in incorporating crop and weed residues into the soil.

The tip of the tines can be equipped with teeth which may be of different shapes; large tools (e.g. goose foot) enhance the uprooting effect on actual weed flora. Any cultivator passage has a weeding action, but it might also stimulate weed seed germination and emergence (Barthelemy *et al.*, 1987; Peruzzi and Sartori, 1997; Mohler, 2001; Bàrberi, 2002; ASAE, 2004).

TILLAGE IN DARKNESS. The technique of doing the final seedbed preparation in darkness has proved to be a valid preventive method of weed control under some conditions. Tillage in darkness has also been referred to as photocontrol of weeds by several authors (Hartmann and Nezadal, 1990; Juroszek and Gerhards, 2004). This technique relies on the fact that many weed species require light to germinate (Hartmann and Nezadal, 1990). The technique consists of doing the last tillage operation for the seedbed preparation in darkness, either during the night or by covering the tillage implement with an opaque material that prevents light from reaching the soil being tilled. In a recent literature review of over 30 different studies, Juroszek and Gerhards (2004) reported that, according to one study, this technique caused a decrease in weed ground cover of over 97% compared with daylight tillage, while, in another study, the same technique caused an increase of 80%. Admittedly this technique gives inconsistent results, but it was found to decrease or delay weed emergence sufficiently to provide a decrease in weed ground cover of slightly less than 30% on average (Juroszek and Gerhards, 2004). Although small, this decrease could be advantageous for the crop by decreasing the intensity of weed control required.

STALE SEEDBED AND FALSE SEEDBED. Tillage can increase weed emergence from the potential weed flora (seed/bud bank) as mentioned previously in this chapter. Consequently, a set of related techniques have been developed to take advantage of this phenomenon, namely stale seedbed and false seedbed techniques. The general procedure consists of ploughing and tilling the field to prepare the crop seedbed while promoting the maximum emergence of weeds. To this end, the soil could even be firmed to promote a greater emergence of weeds by improving soil contact with weed seeds. Once the seedbed has been prepared, crop seeding or planting is delayed in order to allow sufficient time for weeds to emerge and be destroyed (Mohler, 2001).

The stale seedbed technique involves preparing the seedbed as above and, prior to planting the crop, or crop emergence (particularly when crop seeds are characterized by a slow germination: e.g. onion, carrot, spinach, etc), the emerged weeds are destroyed without disturbing the soil in order to minimize further emergence (Mohler, 2001). Traditionally, herbicides have been utilized, but propane flamers can also be used to control weeds. Rasmussen (2003) reports that a stale seedbed where weed flaming was used had a 30% decrease in weed density compared with a control without flaming. A 2- or 4-week delay in planting (stale seedbed with flaming) resulted in 55% and 79% less weeds, respectively, than in the control with no delay and no flaming. Balsari *et al*. (1994) reported a 60% decrease in weed density and percentage of ground cover 16 days after flaming compared with an untreated control.

The false seedbed technique is similar to the stale seedbed technique except that the seedbed is cultivated instead of being left undisturbed. After a period of time sufficient for the weeds to emerge but not develop too much (approximately 1 week), the soil is cultivated as shallowly as possible. The cultivation depth for subsequent operations should not exceed the depth of the first operation, otherwise new weed seeds might be brought to the surface from lower soil levels. When soil conditions and time permit, this procedure can be repeated several times prior to sowing or planting the crop. The false seedbed technique has not been well documented; however, this practice is widespread on organic farms (Mohler, 2001) and a reduction in weed density of 63–85% has been observed in some situations (Gunsolus, 1990; Leblanc and Cloutier, 1996). Riemens *et al*. (2006) report that, depending on location and year, false seedbed prior to planting of lettuce decreased the number of weeds observed during crop growth by 43–83%. In silage maize, a false seedbed created 3 weeks before sowing decreased the density of early-emerging weed species but had an inconsistent effect on late-emerging species depending on the year and/or sowing times (van der Weide and Bleeker, 1998). These techniques result in delayed planting, which can decrease yields (Rasmussen, 2004).

The false seedbed technique is often carried out by means of flex-tine harrows, but it is also possible to use a rolling harrow developed by researchers at the University of Pisa, Italy (Peruzzi *et al*., 2005a). This implement can effectively control weeds, even under unfavourable soil conditions, by tilling superficially and causing significant crumbling of the soil. This harrow is equipped with spike discs placed at the front and cage rolls mounted at the rear. Ground-driven by the movement of the tractor, the front and rear tools are connected to one another by a chain drive with a ratio equal to 2 (Fig. 8.1).

The discs and the rolls can be arranged in two different ways on the axles. They can be tightly placed together to superficially till (3–4 cm) the whole treated area for non-selective mechanical weed control in a false seedbed operation (Fig. 8.2), or they can be widely spaced to perform precision inter-row weeding in a row crop (Fig. 8.3) (Peruzzi *et al*., 2005a).

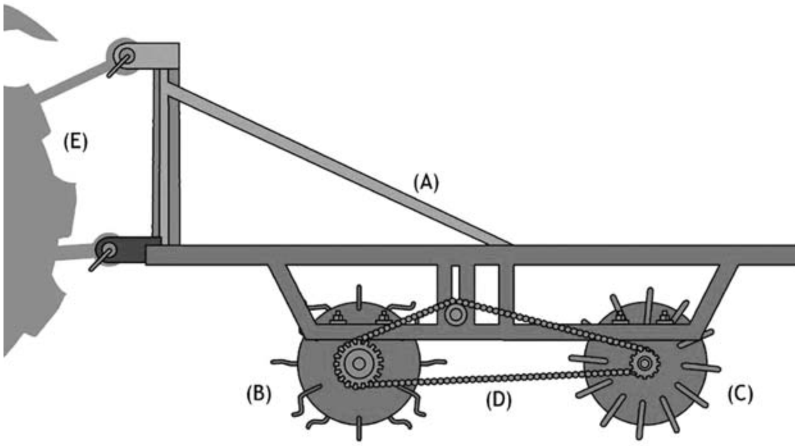

Fig. 8.1. Schematic diagram of the rolling harrow: (A) frame; (B) front axle equipped with spike discs; (C) rear axle equipped with cage rolls; (D) chain drive; (E) three-point linkage. (Drawn by Andrea Peruzzi.)

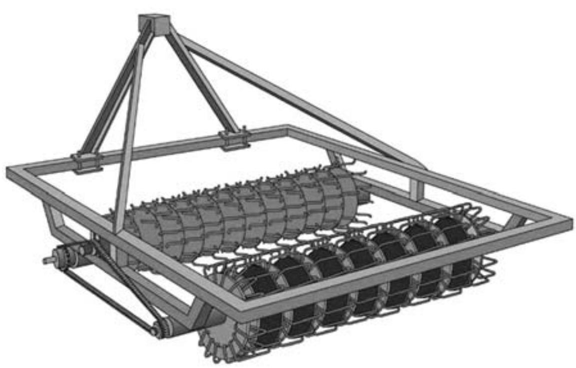

Fig. 8.2. Close arrangement of the tools of the rolling harrow for non-selective treatments. (Drawn by Andrea Peruzzi.)

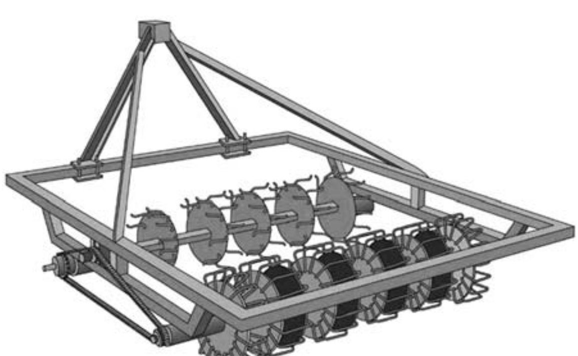

Fig. 8.3. Spaced arrangement of the tools of the rolling harrow for precision inter-row weeding. (Drawn by Andrea Peruzzi.)

The action of the rolling harrow is characterized by the passage of the spike discs that till the top 3–4 cm of the soil followed by the passage of the cage rolls that work at a higher peripheral speed, tilling and crumbling the first 1–2 cm of the soil. These two actions separate weeds from the soil, achieving an excellent level of control. The harrow also stimulates the germination and emergence of new weeds, making it very suitable for the false seedbed technique where the objective is to reduce the weed seedbank and, consequently, the potential weed flora.

The efficacy of the rolling harrow was determined in spinach fields in the Serchio Valley in Tuscany, central Italy, and in carrot, fennel and chicory fields in the Fucino Valley in Abruzzo, southern Italy. When used in a false seedbed, the rolling harrow decreased weed density by approximately 20% more than the flex-tine harrow when assessed after crop emergence. When used for inter-row precision weeding, the steerage hoe equipped with rigid tines decreased weed density by 30–50% more when evaluated 15 days after the treatment (Peruzzi *et al*., 2005a).

RAISED BED CULTIVATION. In many geographical areas of Europe, the cultivation of vegetables is carried out on raised beds or on strips that are formed every year just before planting. The general intention is to improve growing conditions either by increasing drainage of water for crops susceptible to excess water (e.g. spinach) or by loosening the soil for root crops such as carrot. This technique facilitates the formation of permanent traffic lanes where the tractor wheels always pass, confining soil compaction to a small area (Peruzzi *et al*., 2005b,c).

In these production systems, primary and secondary tillage are generally carried out on the whole cultivated surface. After seedbed preparation, raised beds are formed by specialized equipment or the cultivated area is divided into strips. In conventional cropping systems where herbicides are used, these operations coincide or are immediately followed by planting. In cropping systems based on non-chemical weed control, all field operations preceding planting are performed only on the raised beds, or on the cultivated strips (Peruzzi *et al*., 2005b,c).

Cultivating tillage

Previously referred to as tertiary tillage, cultivating tillage is the term suggested by the ASAE (2004). Cultivating tillage equipment is used after crop planting to carry out shallow tillage to loosen the soil and to control weeds (Cloutier and Leblanc, 2001). These implements are commonly called cultivators.

Soil loosening by cultivators has been proven to improve crop yield even in the absence of weeds (Buckingham, 1984; Leblanc and Cloutier, 2001a,b). This positive contribution to yield could be ascribed to the fact that soil loosening breaks the soil crust when one is present, possibly improving crop development and growth; it also breaks up soil capillaries, preventing water evaporation under warm and dry growing conditions; it can enhance mineralization of organic matter; and improves water infiltration in the soil (Blake and Aldrich, 1955; Souty and Rode, 1994, Buhler *et al*., 1995; Leblanc *et al*., 1998; Cloutier and Leblanc, 2001; Steinmann, 2002).

Cultivating tillage can destroy weeds in several different ways. After a cultivator passes over a field, complete or partial burial of weeds can be an important cause of mortality (Cavers and Kane, 1990; Rasmussen, 1991; Kurstjens and Perdok, 2000). Another mode of action is by uprooting and breakage of the weed root contact with the soil (Cavers and Kane, 1990; Rasmussen, 1992; Weber and Meyer, 1993; Kurstjens *et al*., 2000; Kurstjens and Kropff, 2001). Mechanical tearing, breaking or cutting the plant can also result in mortality (Toukura *et al*., 2006). Cultivation is more effective in dry soils because weeds often die by desiccation and mortality is severely decreased under wet conditions. Cultivating when the soil is too wet will damage the soil structure and possibly spread perennial weeds (Cloutier and Leblanc, 2001).

Cultivators can be classified according to where they are used in a crop. These categories are: broadcast cultivators, which are passed both on and between the crop rows; inter-row cultivators, which are only used between crop rows; and finally, intra-row cultivators, which are used to remove weeds from the crop rows (Cloutier and Leblanc, 2001; Leblanc and Cloutier, 2001b; Melander *et al*., 2005).

BROADCAST: PASSED BOTH ON THE CROPS AND BETWEEN THE CROP ROWS. Broadcast, sometimes referred to as full-field or blind cultivation, consists of cultivating with the same intensity both on and between the crop rows. The cultivations can be done before or after crop emergence. There are several types of harrow that can be used for this type of cultivation but the most common implements used are chain harrows, flex-tine harrows in Europe, and rotary hoes in North America.

Rotary hoes and most other cultivators have often been accused of promoting new weed germination, because it has been observed that there is sometimes a flush of weed emergence immediately after cultivation. Often, on soils that are subject to crust formation, this phenomenon could be better explained by the breaking of the soil crust with the cultivator passage rather than by new weed germination. In fact, Cloutier *et al*. (1996) observed in a field experiment that less than 5% of all germinated weeds in the soil emerged. A large proportion of these weeds were unable to emerge because of the presence of the soil crust (Leblanc *et al*., 1998). Soil crust presence also explains the big flush of weed emergence on a day following rain. This is rarely caused by sudden and rapid weed germination. A more likely explanation is that the soil crust becomes more plastic when moist, offering less resistance to weed emergence. Although breaking the soil crust could be seen as promoting weed emergence, it is generally more beneficial to the crops.

Chain harrows

Chain harrows have short shanks fitted on chains rather than a rigid frame, so that they hug the ground. They are especially effective on light soils and prior to crop emergence, or in short crops.

Flex-tine harrows

The flex-tine harrow is the most commonly used implement in this category in Europe (Fig. 8.4). Because these harrows are rear-mounted on the tractor and not pulled on the soil, they can be used in taller crops and on the top of ridges. Flex-tine harrows have rigid frames and a variety of different tines. They have fine, flexible tines which destroy weeds by vibrating in all directions. Rigid-tine harrows, best for heavy soils, consist of several sets of spikes or rigid blades angled at the tip; the spikes or blades are mounted on a rigid frame or a floating section. The spikes or blades vibrate perpendicularly to the direction in which the tractor is moving. Depending on the model,

Fig. 8.4. Flex-tine harrow in silage maize. (Photo by Wageningen UR Applied Plant Research.)

tension on the tines can be adjusted individually or collectively to change the intensity of the treatment. The working width ranges from 1.5 to over 24 m, but the most common width is 6 m. The driving speed with these harrows varies between 3 and 12 km/h (4 km/h for sensitive crops or stages, with 8 km/h being the more commonly used speed). Cultivation depth can be adjusted by depth wheels on the harrow (when present) or by the tractor's hydraulic system, since they are attached to the three-point hitch. Depth can also be adjusted by changing the tine angles and driving speed.

Pre-crop emergence cultivation with harrows is selective because the crop seeds are planted more deeply than the weed seeds or are larger than the weed seeds, and are therefore not affected or only slightly affected by cultivation (Dal Re, 2003; Peruzzi *et al.*, 2005b). In general, this is a benign treatment that destroys only weeds that are at the white-thread stage (weeds that have germinated but not emerged), dicotyledonous weed seedlings before the two-leaf stage, and monocotyledonous weeds at the one-leaf stage. However, where crop seeds are planted deep enough, tines can be adjusted to be more aggressive (angled forward) and driving speed can be increased to destroy more developed weeds such as small-seeded dicotyledonous weeds with 2–4 true leaves. Fairly aggressive harrowing is possible with deep-sown crops such as beans, peas and maize. However, care is needed with shallow-sown crops such as spring-sown onions and sugarbeet, where cultivation depth is of great importance.

Post-crop emergence broadcast treatment is selective, given the fact that the crop is better rooted. Since the crop has larger seeds (and therefore more energy reserves) or is transplanted, it becomes established faster than the weeds. Harrowing weeds in their earlier stages of development (e.g. until the first true leaves are visible), can result in excellent levels of control. However, harrowing might have to be repeated several times to maintain acceptable weed control levels during the growing season (Rasmussen, 1993). Spring-tine harrows can be used post-emergence in cereals, maize, potatoes, peas, beans, many planted vegetables and relatively sensitive crops such as sugarbeet. In sensitive crops, harrows cannot be used in the early crop growth stages such as before four true leaves in sugarbeet. Cultivation speed should be decreased (e.g. 3–4 km/h) when a crop is at a sensitive development stage such as the two-leaf stage in maize. In this particular case, the tines should be at the vertical setting. Information has been compiled where suggestions are made concerning which harrow or other equipment to choose for various crop growth stages (Fig. 8.5; example taken from van der Schans *et al.*, 2006).

Rotary hoes

The rotary hoe is a harrow with two gangs of hoe wheels that are rolled on the ground (Fig. 8.6). The wheel axles are horizontal and the two sets of wheels are offset for maximum soil contact. High-residue models have a greater distance between the two gangs to prevent the accumulation of plant residues. The hoe wheels have several rigid and curved teeth that are sometimes referred to as 'spoons' because they have a wider point at their tip, similar to a spoon. The teeth penetrate almost straight down but lift the soil as they emerge, pulling young weed seedlings. The selectivity of the rotary hoe is attributed to the crop seeds being deeper than the working depth or of the crop being better rooted than the weeds.

Rotary hoes are implements that are widely used in North America, even by growers who utilize herbicides. They use the rotary hoe to incorporate herbicides into the soil and to break the soil crust when one is present. Rotary hoes can be used to cultivate a field relatively quickly and cheaply (Buckingham, 1984; Bowman, 1997). Their width varies from 3 to 12 m and the optimal speed at which they should be operated varies from 8 to 24 km/h. Extra weights might have to be added because teeth penetration decreases as speed increases. The ideal working depth of the rotary hoes varies between 2 and 5 cm. They can be passed before or after crop emergence. They are most effective against weeds at the white-thread stage but, with the exception of monocotyledonous weeds, will control many weed species at the two-leaf stage. Crops such as maize, soybean and various field beans tolerate one or several cultivations with the rotary hoe (Bowman, 1997; Leblanc and Cloutier, 2001a,b). It is often recommended to increase the seeding rate of crops that receive multiple cultivations with the rotary hoe to compensate for some of the crop uprooting that can occur.

INTER-ROW CULTIVATION. The use of inter-row cultivators is generally widespread and well mastered. These implements are used in row crops by conventional growers as well as growers who do not use herbicides. There is minimal risk to the crop and weed control is generally excellent. The only limitations are crop height and growth stage because of tractor and cultivator ground clearance and potential damage to crop foliage. Also, because of critical periods of weed interference, it is preferable to carry out inter-row cultivations early rather than late in the season. Another problem with late cultivations is that when weeds are well developed, cultivators could easily get plugged with plant material. Cultivator shields can be used early in

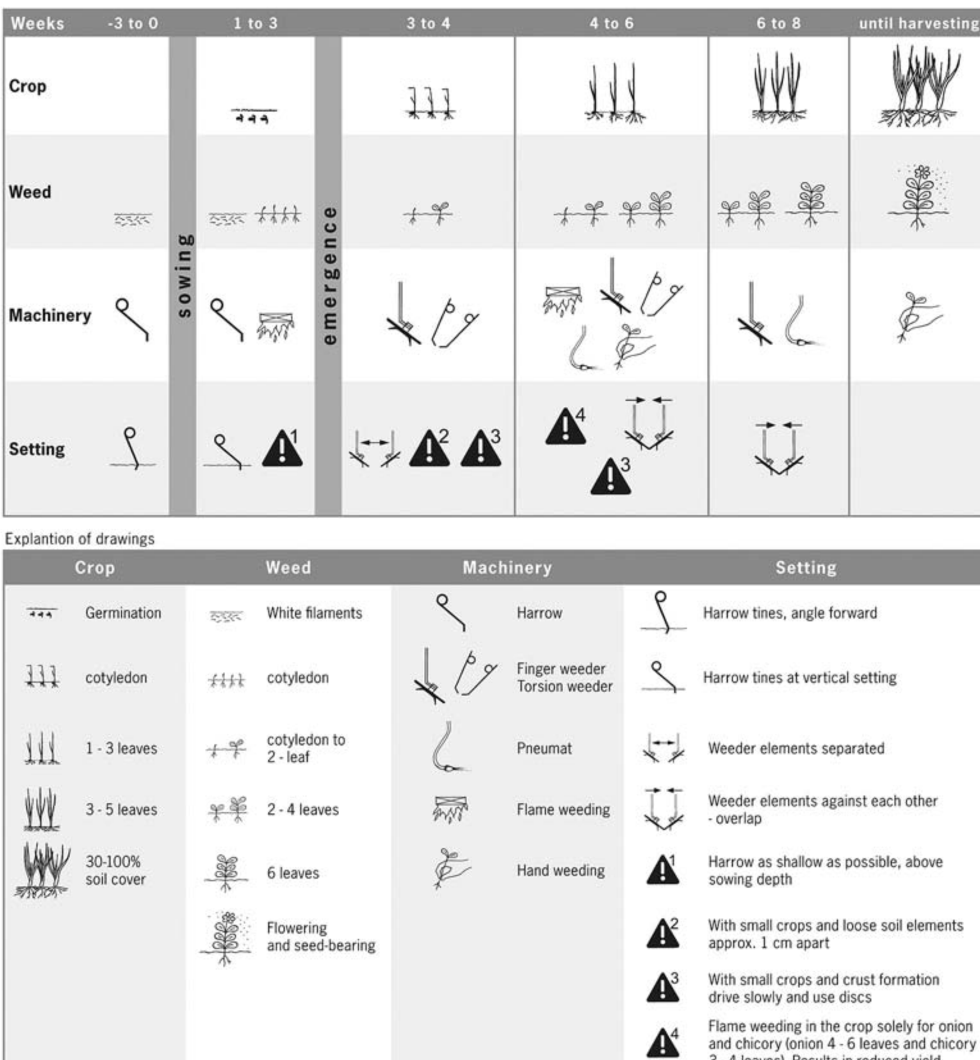

Fig. 8.5. Example taken from van der Schans *et al.* (2006). Possibilities and machine settings for weed control in crop rows for small seed crops, tightly spaced, such as carrots, chicory, onions, red beet and spinach.

Fig. 8.6. Rotary hoe in action in cereals. (Photo by Maryse Leblanc.)

the season to prevent accidental burying or breaking of crop seedlings by soil or plant residues thrown by the cultivator. Cultivator shields come in a variety of forms. There are rolling, panel, tent and wheel shields that move along each side of the crop row (Bowman, 1997; Cloutier and Leblanc, 2001).

Inter-row cultivation can be carried out by inter-row cultivators, discs, brush weeders, rotary cultivators, rolling cultivators, basket weeders and rolling harrows.

Inter-row cultivators

Inter-row cultivators were the earliest and are the most widespread type of cultivators used in row crops. In general, mechanical weed control between crop rows is carried out with a group of cultivating tools (usually on three to five shanks, called a gang) mounted on a toolbar, one gang per inter-row. Ideally, the implement should cultivate the same number of inter-rows that were represented by one planter pass, or a whole fraction, because adjacent planter passages are seldom totally parallel and equidistant. The width of the toolbar and the number of blades depends on the width of the working passage and on the row distance of the planting or sowing machine. Cultivating as much of the inter-row area as possible without damaging the crop should be the objective of inter-row cultivation. The distance between the crop rows and the precision of the implement determine the working width of the gangs. Some accidental crop damage might occur when working very close to the crop rows, in the presence of soil crust, or when high tractor speeds are used (Bowman, 1997; Mohler, 2001).

The gangs mounted on the toolbar can either have rigid or vibrating shanks to which various types of points (shovels, sweeps and weed knives) can be attached. These points vary in width from a few centimetres to 76 cm. Each tool consists of a shank which is typically long and narrow. The shank ends in a point and connects to the toolbar or the frame (Cloutier and Leblanc, 2001). An assortment of different cultivating tools can be fitted between two crop rows when the distance between the rows is 25 cm or more. The major benefit offered by this approach is the ability to adjust gangs to fit any inter-row width. Alongside the working width of the cultivating tools, the type of soil cultivation attained is also of importance. The ideal cultivation depth is less than 4 cm because there is a risk of crop root pruning if cultivating too close and too deep. Inter-row cultivators have been classified as being adapted for low (up to 20%), moderate (up to 30%), high (up to 60%) and maximum residue levels (up to 90%) (Bowman, 1997).

Cultivators using vibrating shanks are usually considered light-duty cultivators. These shanks can be C-curved or S-shaped; commonly referred to as Danish S-tines. Various types of sweeps (duckfoot, goosefoot, triangular, backland, etc) can be attached to the shanks. The S-shaped shanks vibrate vigorously, shatter the soil and kill weeds, while the C-curved shanks vibrate considerably less (Bowman, 1997). The greater the speed, the more aggressive the tools with vibrating shanks will cultivate and the more they could stimulate the germination of new weeds.

Inter-row cultivators with rigid shanks are considered heavy cultivators, better used in fields with high residues. These cultivators cut off weeds and disturb the soil to a lesser extent than cultivators with vibrating shanks. An implement with rigid shanks will disturb soils the least when passed at an approximate speed of 6 km/h. Wide, sharp sweeps can be attached to these shanks. This type of cultivator is more effective against bigger weeds than the ones with vibrating shanks.

Mounting gangs on a parallelogram with a gauge wheel ensures that soil contours are followed closely. The best uniform hoeing depth can be achieved with a minimum distance between the gang and the gauge. The location of the toolbar relative to the tractor and steering systems is discussed in a separate section below.

Discs

Although discs alone are sometimes used to replace shanks and points on gangs, they are usually mounted on gangs with shanks and points to cultivate very close to the crop row while other weeding tools cultivate the rest of the inter-row. Some implements might require a second operator to guide the gangs in order to increase cultivation precision. Discs can be adjusted to throw soil towards the crop row or to remove soil and weeds away from the row.

Brush weeders

There are several different types of brush weeder. In general, the brushes are made of fibreglass and are flexible (Fig. 8.7). There are horizontal-axis brushes and vertical-axis brushes that are either driven by the tractor's power take-off (PTO) shaft, electric motors or by hydraulics. Working very superficially, these weeders mainly uproot, but do also bury or break weeds. A protective shield panel or tent can be used to protect the crop. In the case of rear-mounted implements, a second operator might be needed to steer the brushes so as to cultivate as close as possible to the crop without damaging it.

When using horizontal-axis brushes, their rotation speed should be only slightly faster than the tractor speed, otherwise too much dust will be generated. A higher rotational speed will not improve the effect; however, the bristles will wear out more rapidly. The soil must not be too hard or too fine. When the soil is too hard, the brush weeder will remove only the part of the weeds above the soil, and the weeds will readily regrow. When the soil is too hard for hoeing, brush weeders can be used to remove the part of the weeds above the soil. When used on moist soil, the effect will diminish as a result of soil sticking to the bristles.

Some models of vertical-axis brushes can have the angle, rpm and rotating direction of the brushes adjusted. Vertical-axis brushes can be adjusted to throw soil towards the crop row or to remove soil and weeds away from the row (Fogelberg and Kritz, 1999).

Rotary cultivators

Rotary cultivators refer to rotary tilling cultivators which have multiple heads (one per inter-row) and rotary tillers which have a single head that covers several inter-rows. Driven by the tractor's PTO, the cultivators have a vertical, horizontal or oblique axis. Designed for shallow tillage, the inter-row gangs are made of blades, points or knives that rotate at high speed just below the soil surface (Bowman, 1997). Rotary cultivators can cultivate close to the crop row and they are very effective in controlling weeds. However, implements with horizontal axes require time-consuming adjustments, or else gangs with specific working widths must be available for each inter-row distance. The working width of the Weed-fix cultivator (Fig. 8.8), a rotary cultivator with vertical axis, can be adjusted by moving the two rotors closer to or further from each other.

Rolling cultivators

Rolling cultivators have gangs of wheels that are ground-driven. The wheels can be 'spiders'

Fig. 8.7. Vertical axis brush weeder. (Photo by Wageningen UR Applied Plant Research.)

(curved teeth), notched discs, 'stars' etc. There are three to five discs per gang and gangs can be arranged to throw soil towards or away from the crop row. Because gangs are mounted diagonally from the crop row, there are generally two gangs of wheels per inter-row (Lampkin, 1990; Bowman, 1997).

Basket weeders

Basket weeders, also referred to as rolling cages, are cylindrical, made of quarter-inch spring wire, and ground-driven (Fig. 8.9). These cultivators are pulled rather than rear-mounted on a tractor. Ground-driven by the movement of the tractor, the front and rear tools are connected to one another by a chain drive with a ratio equal to 2. The first set of baskets loosens the soil and the second pulverizes it, uprooting young weed seedlings.

Rolling harrows

The disposition of the tools of the rolling harrow enables it to perform efficient selective inter-row weed control (see Fig. 8.3). Young weed seedlings are controlled because they are uprooted from the soil, even if it is very wet and plastic. To enhance the precision and the weeding action, particularly important when vegetable crops are cultivated, the implement may be equipped with a manual guidance system. Moreover, the rolling harrow may be equipped with flexible tools that can selectively control weeds in the rows. This type of precision hoeing is very effective because it

Fig. 8.8. Photo of the Weed-Fix cultivator, a vertical-axis rotary cultivator. (Photo by Wageningen UR Applied Plant Research.)

Fig. 8.9. Photo of the Buddingh basket weeder Model K used in carrots. (Photo by Daniel Cloutier.)

makes it possible to selectively perform a post-emergence treatment on the whole cultivated surface. Thus, this implement is multipurpose and versatile, as it can be used for false seedbed and for precision hoeing (Peruzzi *et al*., 2005a).

Guidance systems

Guidance systems (mechanical or electronic) allow cultivation to be done at greater speeds and reduce the risk of crop damage. Also, it is possible to cultivate more of the inter-row area by using these systems. Hoeing 1 cm closer to the row will, in the case of onions planted in 25 cm spaced rows, keep an additional 6.5% of the field clean of weeds. This will save between 10 and 30 hours of weeding per hectare in organically grown onions. Consequently, a guidance system that steers accurately in combination with the maximum cultivation width will result in reduced manual weeding costs.

The benefit of weed control increases with every additional centimetre of cultivated intra-row space. The uncultivated strip in which the crop grows must be as narrow as possible while minimizing the amount of crop damaged by the weeding equipment. Intra-row weeders such as finger and torsion weeders achieve better results when the weeders are kept in the same position relative to the crop row. When an operator is driving and steering unassisted, an extra 3–4 cm of clearance from the crop row is required in order to prevent damage to the crop. Consequently, a strip of at least 6–8 cm will not be cultivated in the row. More accurate steering can reduce the uncultivated strip to approximately 4 cm wide.

Steering systems have been developed for the accurate control of weeding machinery. With toolbars mounted on the front of tractors, the driver has an excellent view of the toolbar and the crop rows, and there is sufficient space for the machinery. However, the disadvantage is that a minor correction in the direction in which the tractor is moving results in a much greater correction in the position of the inter-row cultivator. A toolbar mounted between the front and rear wheels of the tractor can be steered with much greater accuracy. However, most tractors offer insufficient space; moreover the driver in the cabin has an insufficient view of the underside of the tractor. Although special implement carriers have been developed for cultivating machinery, their high costs have resulted in little interest in their use. When weeding machinery is mounted on the rear of the tractor, the driver cannot see anything that is happening behind; consequently a distance of 8 cm or more often has to be maintained between the crop rows and the blades of the intra-row cultivator. This results in combined uncultivated strips of at least 16 cm wide around the crop row.

However, for horticultural crops, the accuracy required for operating near the row is sometimes achieved by having a second person seated on a rear-mounted cultivator to steer it.

Mechanical steering systems

The implement must be level to function adequately and the cultivator must also be able to move freely. Some knowledge and experience with the adjustments of the cultivator settings is required. This system will not achieve an optimum effect in the case of differences in soil structure, uneven soil or the presence of ruts.

Weeding equipment mounted rigidly to the front of the tractor responds with an amplified movement following the driver's steering correction. Consequently this makes the steering inaccurate.

The Mutsaert QI steering system resolves this shortcoming; the centre of rotation of the cultivators is located immediately behind the toolbar (van der Schans *et al*., 2006). If a driver makes a steering correction, the result is a smaller adjustment of the cultivator position. The driver is then able to steer as accurately as with a toolbar mounted between the front and rear wheels of a tractor or implement carrier. Cultivating close to the crop rows is also possible by allowing the cultivator to be guided by the crop. This originally required a fairly strong crop (such as maize or beans at a height of about 10 cm). However, the system has now been improved to the extent that even beet plants with four leaves and the ridges of furrow drills can be used to control the guides. Unfortunately, this steering system cannot be combined with the finger or torsion weeders. Furthermore, there are also mechanical systems where guide wheels follow ridges or grooves or deep furrows created at seeding (Bowman, 1997).

Electrical systems

During the past few years, considerable progress has been made with systems using cameras and software to process images acquired live and processed in real-time. An overview of the systems available in Europe has been presented by van der Schans *et al*. (2006). These systems consist of a camera which locates the crop row(s) a few metres in front of the cultivator. The camera is mounted on a toolbar. Software uses the image to calculate the row position. The toolbar is mounted on a side-shift fitted to the tractor. A side-shift consists of two parts: a front frame attached to the tractor's three-point hitch, which is fixed, and a rear plate to which the implement is attached (Bowman, 1997). The rear plate is hydraulically moved right or left. The side-shift's controls correct the position of the camera and, in so doing, the position of the inter-row cultivators relative to the crop row.

Systems using image recognition to determine the position of individual crop plants are under development. When there is sufficient space between crop plants in the row, a cultivator or a flame weeder can then be used to cultivate or burn weeds between crop plants.

INTRA-ROW CULTIVATION

Finger weeders

The original finger weeder is the Buddingh Model C (USA). It has two pairs of truncated steel cones that are ground-driven by metal tines that point vertically. Each cone has rubber spikes or 'fingers' that point horizontally outwards. The crop row is between each pair of cones. The rubber fingers from opposite cones connect together in the row, pulling out small weeds in the process. The space between opposite cones can be widened to prevent crop damage. This type of cultivator is effective against young weed seedlings and is gentle to the crop provided that it is well rooted. Finger weeders have been imported and modified by various European manufacturers (Fig. 8.10).

Compared to the harrow, finger weeders have the disadvantage that they need very accurate steering to work as close as possible in the crop rows, and thus their working capacity is relatively low. However they are gentler to the crop and can easily be combined with inter-row cultivation. The finger weeders operate from the sides of the crop row and beneath most of the crop leaves. As with inter-row brush weeding, finger weeders also cause relatively more weed uprooting and move them away from the crop rows. Finger weeders are more effective against weeds with true leaves, but the weeds still need to be small and/or easy to uproot. The tools can be used in many transplanted vegetables, beans, spring-seeded rape, seeded onions (from two-leaf stage and beyond), red beet and sugarbeet (from 2–4 leaves), carrots (two-leaf stage and beyond) and strawberries (Bowman, 1997; van der Schans *et al.*, 2006).

Torsion weeders

Intra-row weeding using the torsion weeder is selective because the crop is better rooted (and better anchored) than the weeds. Torsion weeders are made up of pairs of spring tines connected to a rigid frame and bent in various ways (e.g. angled downward and back towards the row) so that two short segments (only a few centimetres long) work very close together and parallel to the soil surface, even overlapping over the crop plants (Fig. 8.11). The coiled base allows tips to flex with soil contours and around established crop plants, uprooting young weed seedlings within the row (Ascard and Bellinder, 1996; Bowman, 1997; Bleeker *et al.*, 2002; Melander, 2004).

The diameter of the spring tines may vary from 5–6 mm to 9–10 mm, increasing the

Fig. 8.10. Finger weeders, manufactured in Europe, operating in transplanted cabbages. (Photo by Wageningen UR Applied Plant Research.)

aggressiveness of the treatment. The adjustments (degree of compression and distance of the spring tines from the cultivated plants) of torsion weeders must be done in the fields, taking into account crop stage and resistance to uprooting, weed sensitivity and soil conditions. Torsion weeders are often used in combination with precision cultivators equipped with a guidance system in order to perform a post-emergence, selective, gentle and very precise weeding treatment on the whole surface in only one passage. Torsion weeders were tested both in Europe and in North America on many herbaceous and horticultural crops with very good results in terms of intra-row weed control; consistently reducing the time required to finish weed removal in the rows by hand-pulling and/or manual hoeing (Ascard and Bellinder, 1996). This tool was also used with very good results in poorly rooted vegetable crops such as carrot, reducing weed density in the rows by 60–80% (Peruzzi *et al*., 2005b).

Other flexible tools for intra row cultivation

There are other flexible tools (spring-hoe weeders or flats) that can be used in a similar way to the torsion weeders in that they work within the crop rows, exploiting the vibration around their vertical axis to selectively control weeds at the white-thread stage. Selectivity is also determined by the difference in anchorage existing between crop plants and weeds. Again, as for the torsion weeders, the adjustment of the flexible tools must be determined in the fields, taking into account crop growth stage and resistance to uprooting, weed sensitivity and soil conditions. The available assortment of different flexible implements, including torsion weeders, ensures that some tool will be available for use with different crop and weed types and anchorage, density, growth stages and development, aggressiveness, soil type and field conditions (Bowman, 1997; Mohler, 2001; Melander, 2004; Peruzzi *et al*., 2005b,c).

Spring-hoe weeders are set up similarly to the torsion weeders except that they are in paired sets and the weeding section is a long flat metal blade that is driven along the crop row. The blade is held vertically instead of horizontally. The weeding effect is obtained by the uprooting of weeds when the blades move slightly below the soil surface. Being less flexible than the torsion weeders, they are more aggressive and can be used in well-established crops (Bowman, 1997).

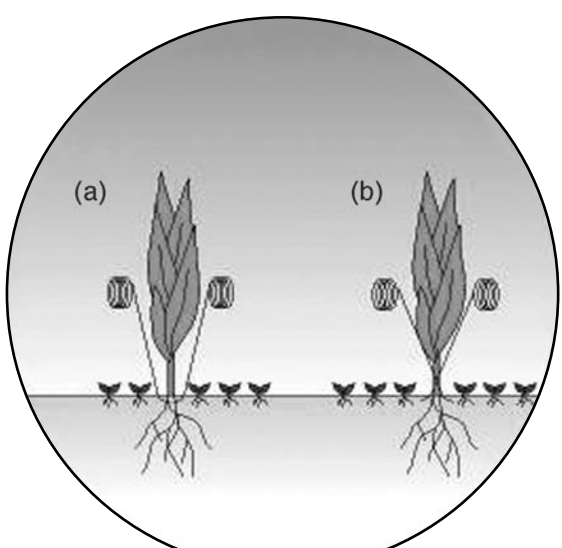

Fig. 8.11. Schematic diagram of torsion weeder action with different adjustments: (a) tines close to crop plants; (b) tines crossed on crop plants. (Drawn by Andrea Peruzzi.)

An implement has recently been developed that uses vibrating teeth made up of steel spring tines bent downward horizontally and then bent toward the soil surface with a first angle of 135° and a second angle of 45° in order to have two segments 5–10 cm long to work (vibrating around their axis) within the rows and very close to crop plants (Fig. 8.12). The tension of the vibrating teeth and distance from the cultivated plants must be adjusted, taking field conditions into account. The action of these tools is similar to the torsion weeders but less aggressive. Consequently, it is possible to perform intra-row weeding without damaging the crop, even if it is poorly anchored, provided that it is better rooted than the weeds (Peruzzi *et al*., 2005b,c).

Another type of flexible tool, recently built and developed in Italy, is made up of three pairs of vertical spring tines of 6 mm diameter, mounted on a horizontal bar. This set-up makes the two internal tines of the two external pairs vibrate and work in concert with the central pair within the rows and very close to crop plants (Fig. 8.13). Tool adjustment for the intensity of pressure against weeds is simple, while their distance from the cultivated plants must be adjusted by changing their position on the horizontal bar (see also Fig. 8.3). These tools were created to be mounted to rolling harrows used as precision cultivators in order to perform considerable intra-row weeding action. The results obtained on transplanted vegetable crops, such as fennel and chicory, are very encouraging and on the same level as those obtained with torsion weeders (reduction of weed density by about 80%) (Peruzzi *et al*., 2005a).

Pneumat

The Pneumat weeder is an inter-row cultivator that also controls weeds on the crop row by using compressed air to blow small weeds out of the row (Fig. 8.14). Nozzles are placed on each side of the crop row, slightly staggered so as not to blow at each other, cancelling their action. Some results indicate that there could be additional advantages of using the Pneumat in crops with widely spaced rows, such as tulip, or in situations with more developed weeds that have several leaves. The crop must pass precisely through the Pneumat's nozzles. The intensity of the cultivation increases with decreasing distance between the nozzles and increasing air pressure. The crop damage decreases with increasing tractor speed. A pressure of as much as 1 MPa can be used with crops that are extremely well rooted. In that case, even weeds with several true leaves can be controlled. The best effect is obtained when cultivator working depth, air pressure and tractor speed are adjusted according to crop growth stage and field conditions. The tractor's power might become limiting because the air compressor requires a lot of power, in particular when several crop rows are treated at the same time.

Ridging the crop

Another way of controlling weeds on the crop row is by ridging or hilling the crop. This consists in throwing soil on the crop row by using discs or specialized blades such as wings or ridgers (Fig. 8.15). This technique is being used extensively in various crops such as maize,

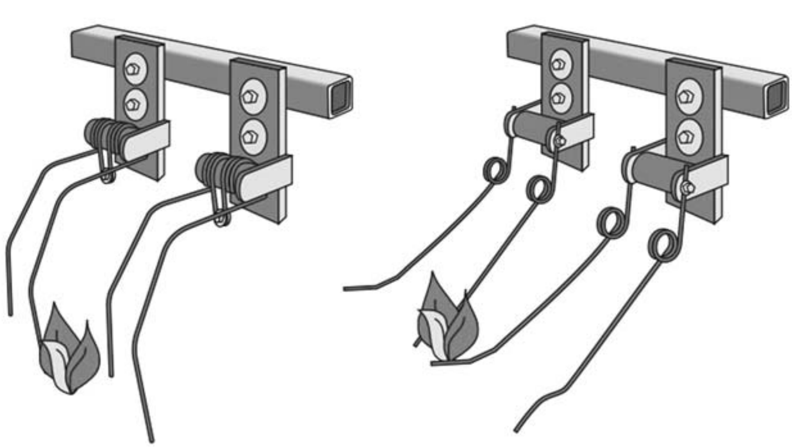

Fig. 8.12. Drawing of the vibrating teeth and torsion weeders. (Drawn by Andrea Peruzzi.)

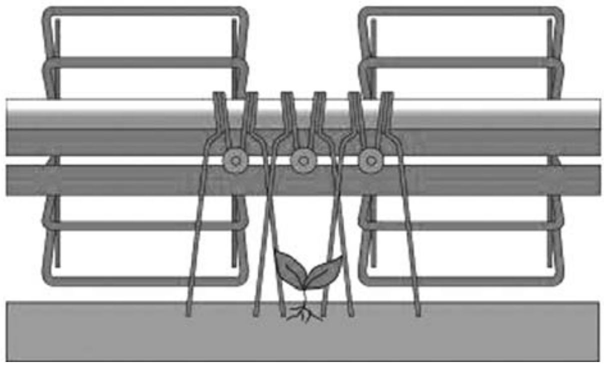

Fig. 8.13. Drawing of the three pairs of flexible tine tools in action. (Drawn by Andrea Peruzzi.)

Fig. 8.14. Blowing away small weeds in seeded onion with the Pneumat. (Photo by Wageningen UR Applied Plant Research.)

Fig. 8.15. Ridging in maize utilizing special wings mounted on an inter-row cultivator. (Photo by Daniel Cloutier.)

sorghum, soybean, potato and leek, among others. It must be done at a crop growth stage that can tolerate partial burial. It is particularly effective when the weeds are completely covered by soil. This technique is used extensively in field crops in North America.

Intelligent weeders

For selective control of well-developed weeds without damaging the crop plants, intelligent weeders are needed. One of the first commercially available new intelligent weeders, the Sarl Radis from France, has a simple crop detection system based on light interception and moves a hoe in and out of the crop row around the crop plants (Fig. 8.16). The machine was designed and built for transplanted crops such as lettuce. It is very effective, but only when weeds are smaller than the crop plants. The working speed is limited to 3 km/h.

Currently several small companies, in cooperation with researchers, are developing other intelligent weeders that use computer vision to recognize crop plants for them to guide weeding tools in and out of the crop row. Denmark (Melander, 2004) and Germany (Gerhards and Christensen, 2003) are focusing on developing sensors or cameras to distinguish between crop and weed plants. The University College of Halmstad in Sweden has a prototype working in sugarbeet (see http://www2.hh.se/ staff/bjorn/ mech-weed). In the Netherlands, Wageningen University is developing and/or testing different intelligent intra-row weeders together with Danish, German and Dutch companies.

Cropping systems with no soil inversion

Cropping systems with annual soil inversions can have detrimental effects on the environment through erosion (Håkansson, 2003). Cropping systems with no soil inversion require less energy to operate, and conserve soil and water (Wiese, 1985). Another advantage of non-inversion tillage is that the organic matter is kept within the top of the soil profile where it can be most useful to the crop. Traditionally, an increased reliance on herbicides for weed control has been associated with cropping systems with no soil inversion (Wiese, 1985). However, there are some non-inversion cropping systems where weed management can be done mechanically. Examples of these systems are field crop production on permanent ridges, semiarid farming on the Great Plains of North America, vegetable production on permanent raised bed systems, and the Kemink exact soil management system, among others.

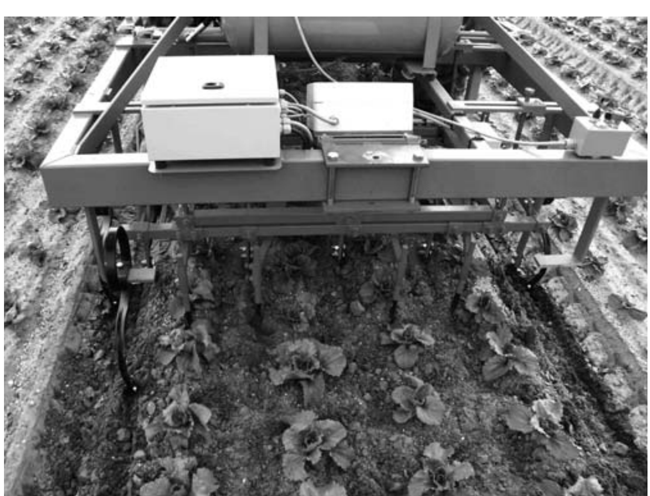

Fig. 8.16. Intelligent weeder manufactured by Sarl Radis, France. (Photo by Wageningen UR Applied Plant Research.)

Ridge tillage is common in North America with maize and soybean. Other field crops can also be produced on ridges but they require wide inter-row spacing. Ridge tillage can increase yields and economic returns from decreased costs, increased soil warming, drainage and aeration, decreased soil compaction, and decreased nutrient leaching (Mohler, 2001; Henriksen *et al*., 2006). This cropping system consists of planting a crop in a ridge that was built during the previous growing season. At planting, the top of the ridge is cut or scraped approximately 5 cm down, a furrow is opened, seeds are dropped, and the furrow is closed by a press wheel, all in a single operation. When the top of the ridge is cut, the soil, weed seeds and plant debris are thrown in the inter-ridge. The plant material is usually rapidly broken down in this inter-ridge space. Weed control is initially done by using a rotary hoe adapted for high-residue conditions. The rotary hoe will normally only touch and cultivate the top of the ridges. The rotary hoe can be used a few times and, when weeds become taller, an inter-row cultivation can be done while the crop row is protected by shields. Once the crop is sufficiently developed to tolerate partial covering by soil, the ridge is rebuilt by one or several passages of an inter-row cultivator equipped with a special ridging tool. The inter-row cultivation will usually destroy all the weeds present in the inter-ridge space, while the soil projected on the crop row will partially or totally cover the weeds. After harvest the ridges are left intact with the crop stubble until the next growing season.

Non-inversion tillage is extensively used in the semiarid production areas of the Great Plains of North America. A number of non-inversion tillage tools were developed primarily for the purpose of summer fallowing; the practice of tilling the land for an entire growing season to control weeds, conserve moisture and stabilize yields. These tillage implements were designed to maintain crop residues on the soil surface and leave the soil with a higher percentage of large aggregates. The wide-blade sweep plough, developed in southern Alberta, employs V-blades that are approximately 1.5–3.0 m in width and are operated at a depth of 7–14 cm (Bowman, 1997). The sharp blades cut the weeds and the crop plants below ground while leaving approximately 85–95% of the original plant residues on the soil surface. The stubble mulch blade plough is often used for the first tillage after crop harvest, and has V-shaped blades which work at a depth of 7–4 cm. The blades are 1–1.5 m wide and this plough leaves 75–95% of surface residue (Bowman, 1997). The rod weeder is particularly well adapted to work under dry conditions. It is used in final seedbed preparation or for pre-crop emergence cultivation when the crop seeds are deep enough for the rod to pass over them. It is passed 4–6 cm below the surface and its rotating action pulls and uproots weeds, depositing them on the soil surface. The rods can be round, square or hexagonal, vary in width from 2 to 4 m, and are powered by ground-driven systems, PTO or hydraulics (Bowman, 1997).

Raised beds are widely used in horticulture where soil inversion is used as primary tillage. Recently new techniques have been developed using permanent raised beds where no soil inversion occurs (Schonbeck, 2004). The raised bed is planted with a cover crop which is subsequently cut and/or mechanically destroyed by heavy crimper/roller tools, leaving a mulch of plant debris into which a crop is planted, normally by a conventional no-till planter, a subsurface tiller/transplanter, or possibly by a dibber drill (Rasmussen, 2003; Schonbeck, 2004). The raised bed can be rebuilt after crop harvest and/or before seeding a cover crop.

Another non-inversion system that was developed at the end of the 20th century is called the Kemink exact soil management system. Developed in Germany, it is a non-inversion soil management system based on subsoiling, ridging and controlling traffic where weeds are controlled mechanically (Henriksen *et al*., 2005).

Systems with inversion of only the top 5–10 cm of the soil have been developed to provide a suitable seedbed while keeping the organic matter at the top of the soil profile. In these cases, weed control can be done mechanically, as in conventional systems with deep soil inversion. The types of plough that can be used are the ‘spot plough’ (Shoji, 2004), two-layer plough (Lazauskas and Pilipavicius, 2004), shallow ploughs, and shallow ploughs combined with a shank that goes deeper into the soil and to which various types of points, sweeps or blades are attached.

8.3 Cutting and mowing

Cutting and mowing are weed management methods commonly used in turf, in rights of way, in vineyards, in orchards, in pastures and in forage crops. These techniques are used to promote crop establishment, to control weed size and seed production, and to minimize competition with the crop (Schreiber, 1973; Kempen and Greil, 1985; Ross and Lembi, 1985; Lampkin, 1990; Smith, 1995; Frick, 2005; Donald, 2006).

Mowing and cutting are rarely sufficient to totally control weeds but, combined with other management techniques, they can favour the crop to the detriment of weed development. Cutting weeds reduces their leaf area, slows their growth and decreases or prevents seed production. Mowing is most effective against annual weeds and it will also affect stationary, but not creeping, perennial weeds. Dicotyledonous weeds are more vulnerable than monocotyledonous weeds to mowing and cutting.

New tools have been developed to mow weeds in crop inter-rows. For example, Donald *et al*. (2001) have developed a specialized mower to cut weeds between soybean and maize rows. Some of the cutting of weeds on the crop row could be done by lasers (Heisel *et al*., 2002). Laser cutting has been described also as a potential energy-efficient alternative to non-chemical weed control that delays the growth of weeds, decreases their competitive ability, and that eventually kills them. It is concluded that lasers have potential for reducing seed production in certain weed species and may be cost-effective on a field scale, although it is noted that further development is necessary. Regrowth appeared after laser cutting when plant stems were cut above their meristems, indicating that is important to cut close to the soil surface to obtain a significant effect (Heisel *et al*., 2001). Water-jet cutting using water at very high pressure (2000–3000 bar) using 5–25 l/min could also be an efficient way to cut weeds (Fogelberg, 2004).

8.4 Pulling

Several mechanical weed pullers have been developed to remove weeds that grow taller than the crop (Anonymous, 1979; Wicks *et al*., 1995). Most rely on rubber tyres rolling together in opposite directions. The stems of the weeds are pulled by the tyres and are either uprooted or broken where they are in contact with the tyres (Fig. 8.17). A moist soil will facilitate the uprooting of the weeds. Although this technique is faster than removing weeds by hand, it should not be used as a primary weed control technique but rather as a last attempt at removing weeds that have escaped other weed control efforts in

Fig. 8.17. Weed puller developed to pull wild mustard from soybean fields in south-western Quebec. (Photo by Daniel Cloutier.)

the course of the growing season. Since it must be used in the field when weeds are growing above the crop, this involves a very late machinery passage, with the risk of the tractor damaging the crop.

8.5 Economics of mechanical weed management

Economically, mechanical weed management can be profitable when compared with conventional production systems involving herbicides (Wicks *et al.*, 1995; Leblanc and Cloutier, 2001b; Mohler, 2001; Peruzzi *et al.*, 2005a,b). The reverse can be reported in some circumstance, but it is often in a context where there is no added value to the crop. Also, the use of herbicides, compared with mechanical weed management, would probably be uneconomical if the cost of decontaminating the environment from herbicides or their metabolites was to be considered when comparing production and weed control costs. This is not normally done as, in most studies, costs start and finish at the farm gate. Also, government commodity programmes might be unfavourable to the use of mechanical weed control instead of herbicides by decreasing crop insurance or support programme funds when non-conventional weed control methods are used (DeVuyst *et al.*, 2006).

8.6 Summary

Tillage remains the most important technique for mechanical weed management. However, tillage alone should not be relied on as a sole weed control technique but instead it should be part of an overall cropping management strategy. Individual weed control techniques will rarely be sufficient to provide season-long weed control. Rather it is a combination of weed control techniques with cropping management systems that will provide acceptable levels of weed control during a growing season.

Most tillage tools are constantly being improved. One of the current trends in mechanical weed management is the development of automatic guidance systems that improve equipment precision in the field. Eventually, this approach will result in self-guided, self-propelled and autonomous machines that will cultivate crops with minimal operator intervention. To this end, real-time image acquisition and analysis will be performed using one or several video cameras, while GPS-based positioning systems will be used to map fields and crop and weed locations. Another trend is the development of cultivators that will be able to selectively control weeds within the crop row while being assisted by sensors that will enable the machine to differentiate crop plants from weeds in order to be able to selectively destroy the latter.

8.7 References

Anonymous (1979) Bourquin weed puller. *Weeds Today* 10, 11.

ASAE (2004) Terminology and definitions for agricultural tillage implements. *ASAE Standards: ASAE S414 FEB04*, pp. 270–282.

ASAE (2005) Terminology and definitions for soil tillage and soil–tool relationships. *ASAE Standards: ASAE EP291.3 FEB05*, pp. 129–132.

Ascard, J. and Bellinder, R.B. (1996) Mechanical in-row cultivation in row crops. In: *Proceedings of the 2nd International Weed Control Congress*, Copenhagen, Denmark, pp. 1121–1126.

Balsari, P., Berruto, R. and Ferrero, A. (1994) Flame weed control in lettuce crop. *Acta Horticulturae* 372, 213–222.

Bàrberi, P. (2002) Weed management in organic agriculture: are we addressing the right issues? *Weed Research* 42, 176–193.

Barthelemy, P., Boisgontier, D. and Lajoux, P. (1987) *Choisir les outils du travail du sol*. ITCF, Paris, France.

Blake, G.R. and Aldrich, R.J. (1955) Effect of cultivation on some soil physical properties and on potato and corn yields. *Soil Science Society Proceedings* 19, 400–403.

Bleeker, P., van der Weide, R. and Kurstjens, D. (2002) Experiences and experiments with new intra-row weeders. In: *Proceedings of the 5th EWRS Workshop on Physical and Cultural Weed Control*, Pisa, 11–13 March, pp. 97–100.

Bowman, G. (ed.) (1997) *Steel in the Field: A Farmer's Guide to Weed Management Tools*. Handbook Series No. 2, Sustainable Agriculture Network, Beltsville, MD, USA.

Buckingham, F. (1984) *Tillage*, 2nd edn. Deere and Company, Moline, IL, USA.
Buhler, D.D., Doll, J.D., Proost, R.T. and Visocky, M.R. (1995) Integrating mechanical weeding with reduced herbicide uses in conservation tillage corn production systems. *Agronomy Journal* 87, 507–512.
Cavers, P.B. and Kane, M. (1990) Response of proso millet (*Panicum miliaceum*) seedlings to mechanical damage and/or drought treatments. *Weed Technology* 4, 425–432.
Cloutier, D. and Leblanc, M.L. (2001) Mechanical weed control in agriculture. In: Vincent, C., Panneton, B. and Fleurat-Lessard, F. (eds) *Physical Control in Plant Protection*. Springer-Verlag, Berlin, Germany, and INRA, Paris, France, pp. 191–204.
Cloutier, D.C., Leblanc, M.L., Benoit, D.L., Assémat, L., Légère, A. and Lemieux, C. (1996) Evaluation of a field sampling technique to predict weed emergence. Xième Colloque International sur la Biologie des Mauvaises Herbes à Dijon, 11–13 September 1996. *Annales de l'Association Nationale pour la Protection des Plantes* 10, 3–6.
Dal Re, L. (2003) Il controllo non chimico delle infestanti: strategie collaudate [Weed management without chemicals: tested strategies]. *Il Divulgatore* 10, 32–67.
DeVuyst, E.A., Foissey, T. and Kegode, G.O. (2006) An economic comparison of alternative and traditional cropping systems in the northern Great Plains, USA. *Renewable Agriculture and Food Systems* 21, 68–73.
Donald, W.W. (2006) Mowing for weed management. In: Singh, H.P., Batish, D.R. and Kohli, R.K. (eds) *Handbook of Sustainable Weed Management*. Food Products Press, New York, pp. 329–372.
Donald, W.W., Kitchen, N.R. and Sudduth, K.A. (2001) Between-row mowing banded herbicide to control annual weeds and reduce herbicide use in no-till soybean (*Glycine max*) and corn (*Zea mays*). *Weed Technology* 15, 576–584.
Fogelberg, F. (2004) Water-jet cutting of potato tops: some experiences from Sweden. In: Cloutier, D. and Ascard, J. (eds) *6th EWRS Workshop on Physical and Cultural Weed Control*, Lillehammer, Norway, 8–10 March 2004, p. 111.
Fogelberg, F. and Kritz, G. (1999) Intra-row weeding with brushes on vertical axis: factors influencing intra-row soil height. *Soil and Tillage Research* 50, 149–157
Frick, B. (2005) Weed control in organic systems. In: Ivany, J.A. (ed.) *Weed Management in Transition: Topics in Canadian Weed Science, Volume 2*. Canadian Weed Science Society, Sainte-Anne-de-Bellevue, Quebec, Canada, pp. 3–22.
Gerhards, R. and Christensen, S. (2003) Real-time weed detection, decision making and patch spraying in maize, sugarbeet, winter wheat and winter barley. *Weed Research* 43, 385–392.
Gunsolus, J.L. (1990) Mechanical and cultural weed control in corn and soybeans. *American Journal of Sustainable Agriculture* 5, 114–119.
Håkansson, S. (2003) Weeds and weed management on arable land: an ecological approach. CABI Publications, Wallingford, UK.
Hartmann, K.M. and Nezadal, W. (1990) Photocontrol of weeds without herbicides. *Naturwissenschaften* 77, 158–163.
Heisel, T., Schou, J., Christensen, S. and Andreasen, C. (2001) Cutting weeds with a CO_2 laser. *Weed Research* 41, 19–29.
Heisel, T., Schou, J., Andreasen, C. and Christensen, S. (2002) Using laser to measure stem thickness and cut weed stems. *Weed Research* 42, 242–248
Henriksen, C.B., Rasmussen, J. and Søgaard, C. (2005) Kemink subsoiling before and after planting. *Soil and Tillage Research* 80, 59–68.
Henriksen, C.B., Rasmussen, J. and Søgaard, C. (2006) Ridging in autumn as an alternative to mouldboard ploughing in a humid-temperate region. *Soil and Tillage Research* 85, 27–37.
Juroszek, P. and Gerhards, R. (2004) Photocontrol of weeds. *Journal of Agronomy and Crop Science* 190, 402–415.
Kempen, H.M. and Greil, J. (1985) Mechanical control methods. In: Kurtz, E.A. and Colbert, F.O. (eds) *Principles of Weed Control in California*. Thomson Publications, Fresno, CA, USA, pp. 51–62.
Kouwenhoven, J.K. (2000) Mouldboard ploughing for weed control. In: Cloutier, D. (ed.) *4th EWRS Workshop on Physical and Cultural Weed Control*, Elspeet, The Netherlands, pp. 19–22.
Kurstjens, D.A.G. and Kropff, M.J. (2001) The impact of uprooting and soil-covering on the effectiveness of weed harrowing. *Weed Research* 41, 211–228.
Kurstjens, D.A.G. and Perdok, U.D. (2000) The selective soil covering mechanism of weed harrows on sandy soil. *Soil and Tillage Research* 55, 193–206.
Kurstjens, D.A.G., Perdok, U.D. and Goense, D. (2000) Selective uprooting by weed harrowing on sandy soils. *Weed Research* 40, 431–447.

Lampkin, N. (1990) *Organic Farming*. Farming Press Books, Ipswich, UK.

Lazauskas, P. and Pilipavicius, V. (2004) Weed control in organic agriculture by the two-layer plough. *Zeitschrift fur Pflanzenkrankheiten und Pflanzenschutz* 19 (Special Issue), 573–580.

Leblanc, M.L. and Cloutier, D.C. (1996) Effet de la technique du faux semis sur la levée des adventices annuelles [Effect of the stale seedbed technique on emergence of annual weeds]. Xième Colloque International sur la Biologie des Mauvaises Herbes à Dijon, 11–13 September 1996. *Annales de l'Association Nationale pour la Protection des Plantes* 10, 29–34.

Leblanc, M.L. and Cloutier, D.C. (2001a) Susceptibility of row-planted soybean (*Glycine max*) to the rotary hoe. *Journal of Sustainable Agriculture* 18, 53–61.

Leblanc, M.L. and Cloutier, D.C. (2001b) Mechanical weed control in corn (*Zea mays* L.). In: Vincent, C., Panneton, B. and Fleurat-Lessard, F. (eds) *Physical Control in Plant Protection*. Springer-Verlag, Berlin, Germany, and INRA Paris, France, pp. 205–214.

Leblanc, M.L., Cloutier, D.C., Leroux, G.D. and Hamel, C. (1998) Facteurs impliqués dans la levée des mauvaises herbes au champ [Factors involved in emergence of weeds in the field]. *Phytoprotection* 79, 111–127.

Melander, B. (2004) Nonchemical weed control: new directions. In: *Encyclopedia of Plant and Crop Science*. Marcel Dekker [doi: 10.1081/E-EPCS-120020279, pp. 1–3, accessed 26 May 2006].

Melander, B., Rasmussen, I.A. and Bàrberi, P. (2005) Integrating physical and cultural methods of weed control: examples from European research. *Weed Science* 53, 369–381.

Mohler, C.L. (2001) Mechanical management of weeds. In: Liebman, M., Mohler, C.L. and Staver, C.P. (eds) *Ecological Management of Agricultural Weeds*. Cambridge University Press, Cambridge, UK, pp. 139–209.

Peruzzi, A. and Sartori, L. (1997) *Guida alla scelta ed all'impiego delle attrezzature per la lavorazione del terreno* [Guide to the choice and the proper use of tillage operative machines]. Edagricole, Bologna, Italy, 255 pp.

Peruzzi, A., Ginanni, M., Raffaelli, M. and Di Ciolo, S. (2005a) The rolling harrow: a new implement for physical pre- and post-emergence weed control. In: *Proceedings of 13th EWRS Symposium*, Bari, 19–23 June.

Peruzzi, A., Ginanni, M., Raffaelli, M. and Fontanelli, M. (2005b) Physical weed control in organic carrots in the Fucino Valley, Italy. In: *Proceedings of 13th EWRS Symposium*, Bari, 19–23 June.

Peruzzi, A., Ginanni, M., Raffaelli, M. and Fontanelli, M. (2005c) Physical weed control in organic spinach in the Serchio Valley, Italy. In: *Proceedings of 13th EWRS Symposium*, Bari, 19–23 June.

Rasmussen, I.A. (2004) The effect of sowing date, stale seedbed, row width and mechanical weed control on weeds and yields of organic winter wheat. *Weed Research* 44, 12–20.

Rasmussen, J. (1991) A model for prediction of yield response in weed harrowing. *Weed Research* 31, 401–408.

Rasmussen, J. (1992) Testing harrows for mechanical control of annual weeds in agricultural crops. *Weed Research* 32, 267–274.

Rasmussen, J. (1993) Yield response models for mechanical weed control by harrowing at early crop stages in peas (*Pisum sativum* L.). *Weed Research* 33, 231–240.

Rasmussen, J. (2003) Punch planting, flame weeding and stale seedbed for weed control in row crops. *Weed Research* 43, 393–403.

Riemens, M.M., van der Weide, R.Y., Bleeker, P.O. and Lotz, L.A.P. (2006) Effect of stale seedbed preparations and subsequent weed control in lettuce (cv. Iceboll) on weed densities. *Weed Research* 47, 149–156.

Ross, M.A. and Lembi, C.A. (1985) *Applied Weed Science*. Burgess Publishing, Minneapolis, MN, USA, 340 pp.

Schonbeck, M. (2004) Organic no-till for vegetable production? www.newfarm.org/features/0104/no-till/index.shtml [accessed 26 May 2006].

Schreiber, M.M. (1973) Weed control in forages. In: Hearth, M.E., Metcalfe, D.S. and Barnes, R.F. (eds) *Forages: The Science of Grassland Agriculture*, 3rd edn. Iowa State University Press, Ames, IA, USA, pp. 396–402.

Shoji, K. (2004) Forces on a model 'spot plough'. *Biosystems Engineering* 87, 39–45

Smith, A.E. (ed.) (1995) *Handbook of Weed Management Systems*. Marcel Dekker, New York, 741 pp.

Souty, N. and Rode, C. (1994) La levée des plantules au champ: un problème mécanique? [Seedling emergence in the field: a mechanical problem?]. *Sécheresse* 5, 13–22.

Steinmann, H.-H. (2002) Impact of harrowing on the nitrogen dynamics of plants and soil. *Soil and Tillage Research* 65, 53–59.

Toukura, Y., Devee, E. and Hongo, A. (2006) Uprooting and shearing resistances in the seedlings of four weedy species. *Weed Biology and Management* 6, 35–43.
van der Schans, D., Bleeker, P., Molendijk, L., Plentinger, M., van der Weide, R., Lotz, B., Bauermeister, R., Total, R. and Baumann, D.T. (2006) *Practical Weed Control in Arable Farming and Outdoor Vegetable Cultivation without Chemicals*. PPO Publication 532, Applied Plant Research, Wageningen University, Lelystad, The Netherlands, 77 pp.
van der Weide, R. and Bleeker, P. (1998) Effects of sowing time, false seedbed and pre-emergence harrowing in silage maize. *3rd EWRS Workshop on Physical Weed Control*, Wye, p. 1 [available at www.ewrs.org/pwc].
Weber, H. and Meyer, J. (1993) Mechanical weed control with a brush hoe. In: Thomas, J.-M. (ed.) *Maîtrise des adventices par voie non chimique: 4th International Conference of the International Federation of the Organic Agriculture Movement*. ÉNITA, Quétigny, France, pp. 89–92.
Wicks, G.A., Burnside, O.C. and Warwick, L.F. (1995) Mechanical weed management. In: Smith, A.E. (ed.) *Handbook of Weed Management Systems*. Marcel Dekker, New York, pp. 51–99.
Wiese, A.F. (ed.) (1985) *Weed Control in Limited-Tillage Systems*. Weed Science Society of America, Champaign, IL, USA.