Mechanical control

Mechanical Weed Control in Agriculture

Daniel C. Cloutier and Marysc L. Leblanc

1 Introduction

Weeds are plants that are considered undesirable in a crop at a given time.Weeds are harmful for a number of reasons. They reduce crop yields, interfere with the harvest, support pathogens and insect pests and contaminate seeds.

Weed control is as old as farming itself. However, progress in mechanized weed management did not begin until the early 18th century, when Jethro Tull invented a seed planter for row crops, which allowed weeds between the rows to be killed by cultivation.

Physical control was the main method used against weeds until herbicides appeared in the mid-20th century (Wicks et al. 1995). Mechanical weed control is a proven technique that kept fields free of weeds long before the advent of herbicides. This technique has experienced somewhat of a rebirth in the past few years. The objective of this chapter is to present the principles behind mechanical weeding and to give some examples to illustrate them.

2 Overview of Physical Control Methods

Physical weed management is based on several different techniques: manual weed removal, pulling, mowing, smothering with mulch, thermal methods (electricity, heat or cold), flooding and tillage.

Manual weed removal and pulling are common around the world, and it has been estimated that 50–70% of the world's farmers control weeds with these methods (Hill 1982; Wicks et al. 1995). Pulling is usually done by hand, although a mechanical weed puller has been developed in the United States to remove tall weeds from a shorter crop (Wicks et al. 1995). In tropical areas, manual removal is often the principal method used, since labour is abundant and cheap. Hand pulling is used for valuable crops for which high labour costs are justified. It can also be employed to eliminate weed escapes (preventing an uncommon weed from becoming widespread), to prevent surviving weeds from producing seed, to destroy a pocket of infestation or to ensure compliance with seed certification programs. Using a hand tool is easier and faster than weeding strictly by hand; tools include various types of hoes and weeding spuds (Clément 1981; Habault 1983).

Mowing and cutting are other weed management methods commonly used in orchards or in establishing forage crops, in the latter case allowing the crop to overgrow the weeds and become better established. These techniques are also used to control the height of weeds and minimize competition with the crop plants in orchards and vineyards (Kempen and Greil 1985). Mowing and cutting are also used to prevent weed seed production (Ross and Lembi 1985).

Mulching is also widely used to control weeds. Mulches are applied before or after the crop has become established. Mulches can be divided into two categories: natural and synthetic mulches. Natural materials used for mulching include straw, sawdust, plant residues and crushed stones, while plastic, paper, cardboard and synthetic fibres are among the synthetic materials used. Mulches prevent weeds from emerging by forming a physical barrier and excluding light. In hot, sunny regions, the use of plastic mulches can also destroy weeds by solarization (Braun et al. 1988; Silveira et al. 1993). This technique consists in leaving plastic mulch, usually clear, on the soil for several weeks during a period of high solar radiation to sterilize the soil and destroy weeds by heat.

Thermal methods may be based on high or low temperatures to kill weeds. Heat-based methods include electricity (Vigneault and Benoit, Chap. 12), infrared radiation, microwaves, hot water, steam and flaming (Ascard 1995). Farmers can choose between nonselective flaming, done over the entire field, or selective flaming, which is done by directing the flamer on the weeds to avoid damaging the crop.

Flooding is another weed control method, often used in rice (*Oryza sativa* L.) and cranberry (*Vaccinium macrocarpon* Ait.) cultivation. Completely submerging the weeds smothers them. When feasible, this technique is very effective (Schlesselman et al. 1985).

After hand weeding, cultivation is the most common mechanical method of weed control.

3 Cultivation

Mechanical cultivation methods for weed control are often divided into three categories: primary, secondary and tertiary tillage (Wicks et al. 1995; Hahn and Rosentreter 1989).

Primary tillage is used to break, turn over, loosen or stir the soil and is the first in a series of treatments to prepare the soil for planting. Primary methods are aggressive. This cultivation is carried out at a considerable depth, leaving an uneven soil surface. Primary tillage destroys any actively growing vegetation, eliminates residues and loosens the soil. This type of tillage controls weeds by burying the seeds (thus preventing emergence) or burying the vegetative reproductive structures of perennial weeds more deeply (destroying or damaging them by exposure to the cold and air). Primary tillage tools comprise mouldboard ploughs, disk ploughs, chisel ploughs and field cultivators.

In secondary tillage, the soil is not worked as deeply as in primary tillage. This type of cultivation is used after ploughing to level the ground, prepare the seedbed and incorporate such substances as fertilizer, lime and manure into the soil. Secondary tillage is also used to destroy weeds before seeding, notably in the stale seedbed technique (Leblanc and Cloutier 1996). This method consists of preparing the seedbed and leaving it for 2 or 3 weeks to encourage the weed seeds to germinate. Then, germinated weeds are cultivated. Secondary tillage equipment includes various types of harrows, cultivators and tillers.

Tertiary tillage consists of hoeing and cultivating during the growing season. Hoeing designates the breaking of the surface crust and loosening of soil around crop plants (Clément 1981). Hoeing aerates the soil, destroys weeds and breaks up soil capillaries, thus preventing the evaporation of water from the soil. In hoeing, the soil is worked at a shallow depth. The purpose of cultivating is to destroy weeds. Hoeing and cultivating are often confused since they involve the same tools and their effects are similar.

4 Cultivators

The term cultivator is used here in a generic sense to refer to machines and tools used for mechanical weed control.

4.1 Mode of Action

Mechanical cultivation destroys weeds in several different ways. After a cultivator passes over a field, the main cause of mortality in weeds is smothering by complete or partial burial (Rasmussen 1992). Cultivators also uproot weeds, exposing the roots at the soil surface (Weber and Meyer 1993). Other actions include breaking the contact between the roots and soil, tearing the plant and depicting the weed seedbank (annuals) or propagules (perennials) (Ross and Lembi 1985). Cultivation is more effective in dry soils. When rainfall occurs right after cultivation, its effectiveness may be reduced because the weeds can reroot. Cultivating in wet soil also causes clods and soil compaction and encourages the spread of perennial weeds.

4.2 Types of Cultivators

Cultivators can be divided into three types: those operated between the crop rows (inter-row cultivators), near the crop rows (near-row cultivators) and across the rows (broadcast or intra-row cultivators). The optimum working depth is generally around 3 cm; however, this depth can be adjusted on most cultivators by means of the tractor's three-point hitch or the depth wheels attached to the cultivator frame. Except in blind (broadcast) cultivation, the cultivator must cover the same number of rows (or whole fraction thereof) as the seeder or transplanter, since two adjacent passes of the seeder or transplanter are never exactly parallel (nor is the spacing between two passes equal to that between two rows done by the seeder). Farmers can avoid the problem by choosing a cultivator with the same width as the seeder or transplanter.

4.3 Inter-Row Cultivation

Inter-row cultivation is by far the most widely used and effective approach. There is minimal risk to the crop and weed control is excellent. With the proper equipment, even shrubs or tree saplings can be destroyed. The only constraints are crop height and growth stage. It is best to perform inter-row cultivation early in the season. Although one late-season pass is feasible, the risk of cutting the crop roots is usually too high. On the other hand, early treatment promotes deep rooting of the crop. When weeds are too well developed, the implements will get clogged with weeds and damage the crop.

Shields can be used early in the season to keep the dirt thrown up by the cultivator from burying or breaking the crop seedlings. Cultivator shields come in the shape of tunnels, protective screens, disks or toothed wheels.

Automatic guidance systems (mechanical or electronic) allow cultivation to be done at greater speeds and reduce the risk of crop damage. In mechanical systems, guide wheels follow the ridges or shallow or deep furrows created during seeding. Electronic systems use sensors or crop-sensing wands that determine the position of the crop row and automatically position the cultivator.

The effectiveness of an inter-row cultivator depends on the proportion of the field that is treated. Since these cultivators cannot go too near the crop row, they can only cover 50 to 70% of the total area. Inter-row cultivators use mainly two types of shanks: vibrating and rigid shanks. Each cultivator consists of a shank, usually long and narrow, which ends in a sweep. The shank connects the sweep to the frame.

4.3.1 Vibrating Shanks

Cultivators using this type of shank are called light-duty cultivators. The most commonly used shanks are Danish S-tines. These shanks are S-shaped and support various types of sweeps, including goosefoot sweeps, uprooting sweeps, and sweeps that are narrow and straight, narrow and curved, or rounded. The shanks vibrate in all directions, pulverizing the soil and killing weeds less than 15 cm high. There are several types of vibrating shanks.

4.3.2 *Rigid Shanks*

Heavy cultivators use this type of shank. The most effective models use a rigid shank to which wide, sharp sweeps are attached. This type of cultivator is effective against shrubs and tree saplings as well as in fields with heavy crop residues, as are common in no-till and ridge-till production systems. However, a more powerful tractor is needed than for other cultivators. The rigid shank type of cultivator is not used for horticultural crops.

4.4 Near-Row Cultivators

Other cultivators are designed to get as close as possible to the crop row using brushes, disks or special blades, which are mounted on one or more toolbars. They are used mainly for horticultural crops. The accuracy required for operating near the row is obtained either by having a second person seated on a rear-mounted cultivator to steer it, or by using an open frame design with one or more toolbars mounted in front of the driver. In the second case, the tractor seal and engine are offset, allowing the driver to see the crop row.

4.4.1 *Brush Weeders*

Brush weeders have a number of common characteristics. The rotating brush are driven by the tractor PTO. The bristles on these rolls are made of fibreglass and are

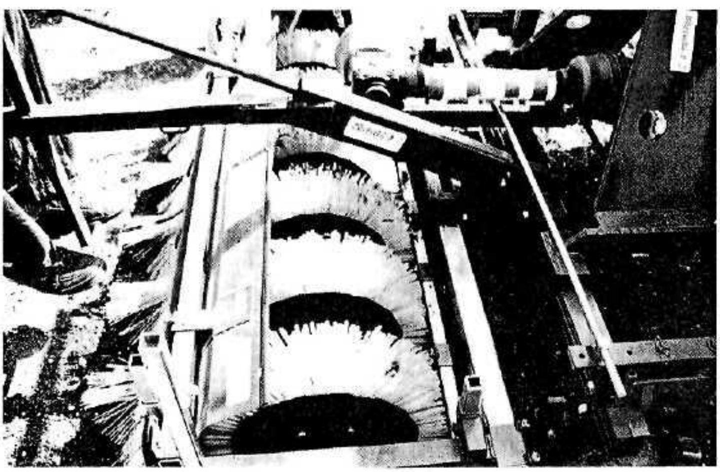

Fig. 1. Horizontal-axis brush weeder manufactured by Bärtschi-Fobro (Switzerland).

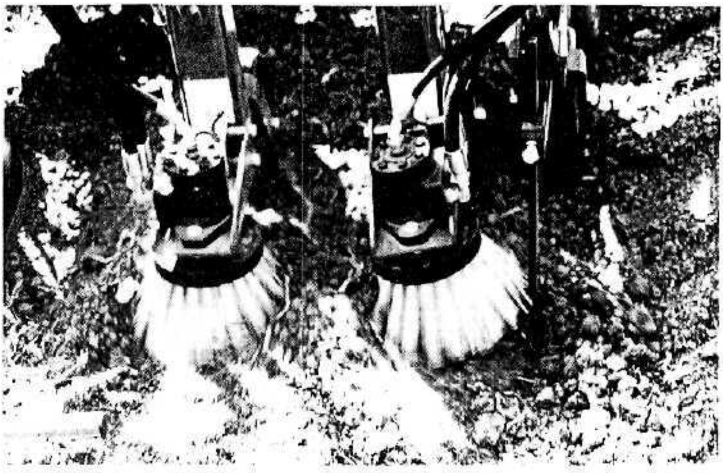

Fig. 2. Vertical-axis brush wecdcr manufactured hy Svensk Ekologimaskin AB (Sweden).

flexible. A second person is needed beside the tractor driver to steer the brushes, so the weeder can go as close as possible to the crop without damaging it.

The brush weeder manufactured by the Swiss company Bärtschi-Fobro uses horizontal-axis rotary brushes, each measuring 50 to 76 cm in diameter. Weeds are killed by uprooting, burial or breaking. The implement has little effect on the crop since its action is focused on the inter-row. The crop plants are covered by a protective tunnel, which keeps them from getting buried (Fig. 1).

Some models such as the Thermec Brush Weeder (Svensk Ekologimaskin AB, Sweden) use vertical-axis brushes. The angle, rpm and rotating direction of the brushes can all be adjusted. The brushes can weed very close to the row or in the row. They can also be used to earth up the crop or remove soil and weeds from the row, depending on the direction in which the brushes rotate (Fig. 2).

4.4.2 Disks

Disks are also used on near-row cultivators. Steered by a second person, they cut the soil very close to the crop plants. They can be operated in well-crusted soils. Shanks are used to weed the inter-row portion.

4.4.3 Blades

Many models of cultivators use various types of blade to control weeds near the crop row. Some require a second person to steer the cultivator manually. One of the first models to be developed has a semi-mounted frame that is steered laterally

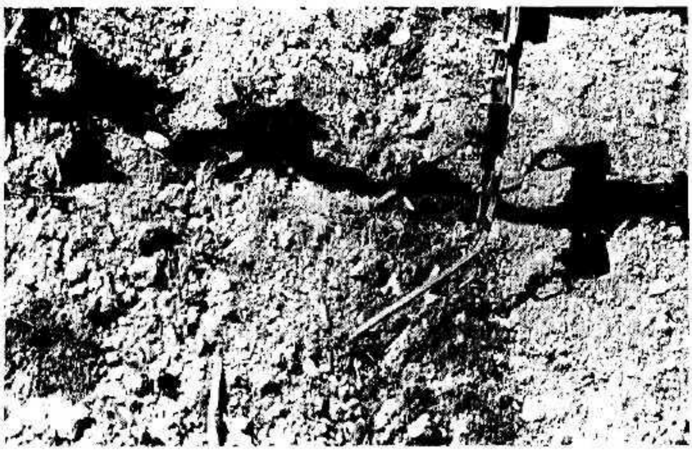

Fig. 3. Flexible blade cultivator, manufactured by Bezzerides (United States).

using pedals that turn Ihe wheels, allowing Ihe cultivator to pass as close as possible to the crop row. The shanks are either fixed or steered by hand.
Systems without manual steering have a toolbar which allows the farmer to adjust the spacing on the cultivator to match the production system in use. The tools used are either traditional shanks or specialised blades. Manufacturers offer a wide variety of implements, Shanks may consist of very sharp blades or square or rounded metal rods ranging from several millimetres to several centimetres thick. The blades can be rigid or curved and highly flexible. Some farmers have created their own blades. Shanks work at ground level or a few centimetres below the soil surface, cutting the weeds as they pass. These cultivators are mounted on tractors with an open front frame design or with offset seats and engines (in the latter case, the engine is offset laterally from the central axis of the tractor, allowing the driver to sec the crop row and the position of the cultivator in relation to the crop row so that any necessary adjustments can be made quickly). One or more rows can be cultivated at the same time (Fig. 3).

4.4.4 Rotary Cultivators

Rotary cultivators are driven by the tractor's PTO and have a vertical, horizontal or oblique axis. They are equipped with blades, points or knives that turn, and pulverize the soil. Used for inter-row weed control, rotary cultivators are very effective and can operate as close to the crop row as horizontal brushes and disks. These wecders are also called rotary tillers or rototillers.

4.4.5 Basket Weeders

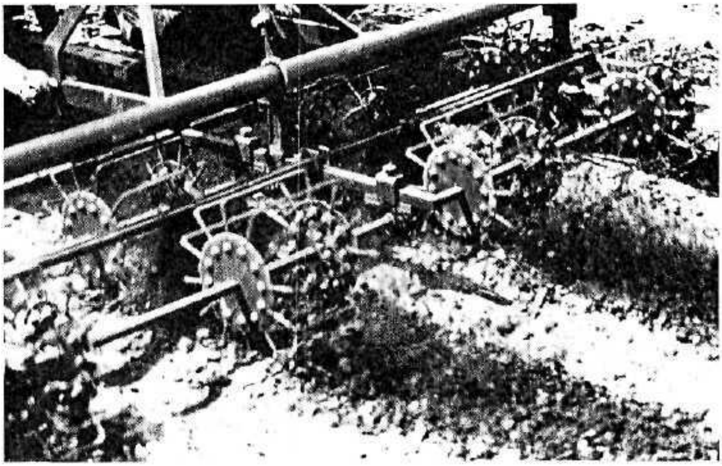

Fig. 4. Basket weeder, **manufactured** by Buddingh (United States).

These cultivators have basket weeders made of quarter-inch spring wire, which rotate at a speed determined by the speed of the tractor as they are pulled over the ground. The Buddingh Model K (United States) (Fig. 4) has two horizontal axles perpendicular to the tractor axis. The axles bear the baskets and are connected to a chain drive that turns the rear rotor faster than the front rotor. The first set of baskets loosens the soil and the second pulverizes it, uprooting the young weed seedlings. The German company Kress also manufactures a basket weeder.

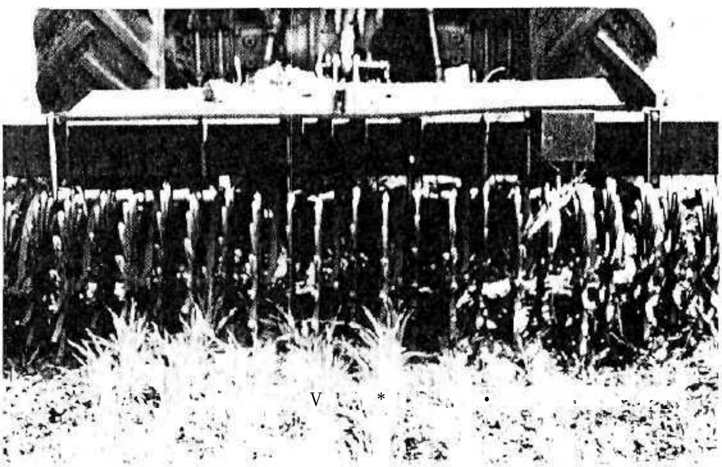

Fig. 5. Rotary hoe, various manufacturers (United Stales).

4.5 Broadcast or Intra-Row Cultivators

Cultivation in the row can be done before or after crop emergence.

4.5.1 Pre-Emergence Cultivation

Broadcast, or blind, cultivation is so named because the cultivator passes over the crop as well as the weeds. The most commonly used cultivators for this type of operation consist of rotary hoes, rigid-tine harrows, flex-tine harrows and chain harrows. The rotary hoe is a harrow with spiked wheels which is pulled by a tractor (Fig. 5). [In France the term is used to designate a rototiller (Habault 1983), i.e. a PTO-driven transverse horizontal rotary cultivator (Clement 1981).] The tool leaves small dents in hard soil. It consists of a set of rolling wheels on a single horizontal axle. Each wheel is mounted on a spring-loaded arm. The arms are attached to the toolbar in such a way that there are two sets of ground driven wheels: one in front that projects the soil and another in back that pulls out and buries the remaining weeds. Each wheel consists of roughly 16 spokes with a spoon-shaped tip (Fig. 6), although the number may vary from one model to another. The implement is usually between 4.6 and 9.5 m wide.

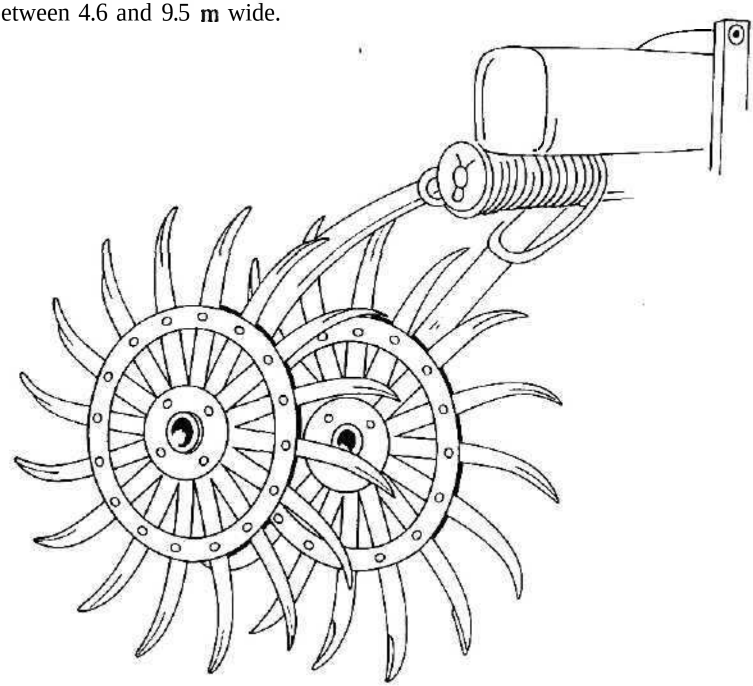

Fig. 6. Drawing of rotary hoe.

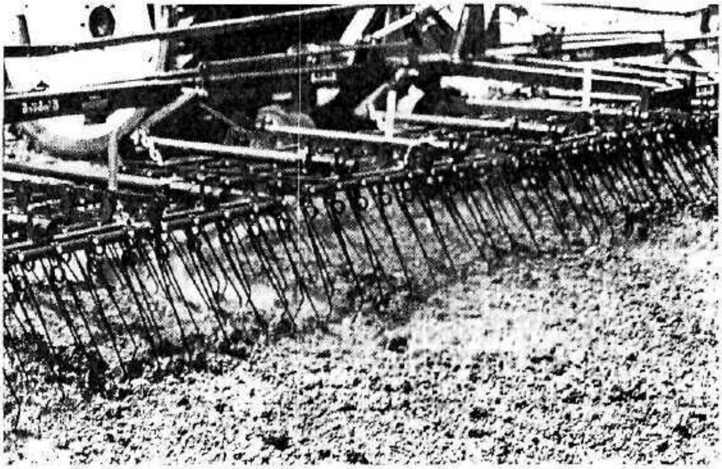

Fig. 7. Flex-line harrow, various manufacturers (Europe).

Chain harrows, or flex-tine cultivators, have short shanks fitted on chains rather than a rigid frame so that they hug the ground. They arc especially effective on light soils. Other harrows have rigid frames and a variety of shanks. Flex-tine cultivators have fine, flexible teeth that destroy weeds by vibrating in all directions (Fig. 7). Rigid-tine harrows, best for heavy soils, consist of several sets of rods or rigid blades angled at the tip (Fig. 8) that are mounted on a rigid frame or floating sections. The rods or blades vibrate perpendicularly to the direction in which the tractor is moving. The tension on the shanks can be adjusted individually or collectively, depending on the model, allowing the farmer to choose the intensity of the treatment. The working width ranges from 4.5 to over 20 m. Cultivation depth

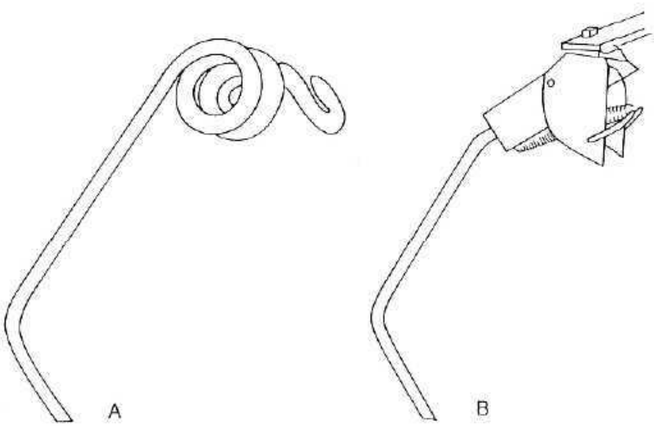

Fig. 8 **A.B.** Harrow shanks: A Flex-tine shank, manufactured hy Hatzenbichler (Europe). **11** Rigid-tine shank, manufactured hy Rabe Werk (Europe).

is adjusted by depth wheels on the harrow or by the tractor's hydraulic system. Rotary hoes and harrows are produced by a large number of manufacturers.
Pre-emergence cultivation 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. This is a gentle treatment that destroys only white-stage weeds, dicot seedlings before the two-leaf stage and monocots at the one-leaf stage. Pre-emergence cultivation is employed in large seeded crops such as corn, cereals, sugar beets, beans and peas,

4.5.2 Post-Emergence Cultivation

Post-emergence broadcast cultivation can be done with a rotary hoe or the various types of harrows described in the previous section. Treatment is selective given the fact that the crop is better rooted than the weeds. Since the crop has larger seeds (and therefore more energy reserves) or is transplanted, it becomes established faster than the weeds. This type of cultivation works well with weeds that have germinated but have not emerged or weeds that are at the one-or two-leaf stage. In this case, rotary hoes can be operated at high speeds, but harrows are pulled slowly to avoid damaging the crop.
The finger weeder, the Buddingh Model C (United States), has weeders shaped like sawed-off cones (Fig. 9). Each cone has rubber fingers that point outwards (horizontally) and metal ones that point downward (vertically). Each pair of cones is used for a single row, with one cone positioned on either side of the row. The cones are ground-driven by the metal fingers which are set back from the row to avoid damaging the crop. They work the soil like a vertical-axis rotary hoe. The rubber fingers mesh together over the row, pulling out the weeds in the process. The dis-

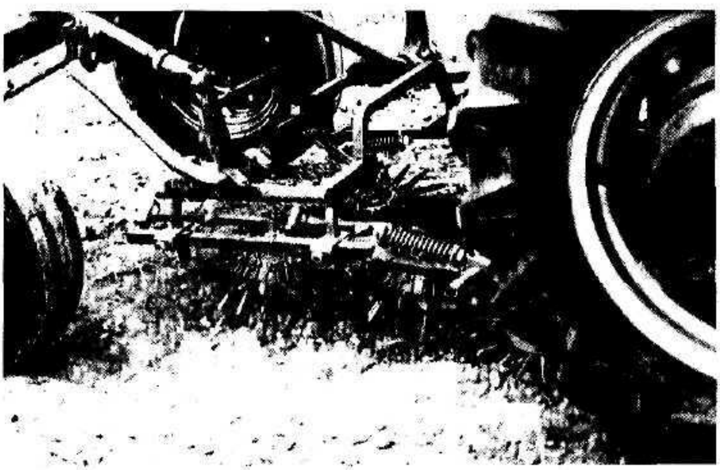

Fig. 9. Intra-row cultivator, Model C, made by Buddingh (United States).

lance between the cones can be adjusted according to the growth stage of the crop. This type of cultivator is effective only against young weed seedlings and is gentle to the crop. Kress, a German company, manufactures this type of weeder loo.
Although most cultivators are designed to minimize the amount of soil thrown onto the crop row, specialized models have been developed solely for that purpose, that is, to ridge or hill the soil. Ridging is used as a production method, while hilling consists of piling soil around the crop. Ridge-tilled corn is an important production system in North America. The principle of the ridger or hiller is the same as that of inter-row cultivators. As the tool passes between the rows, the soil is projected into the row by a hilling sweep, disk or specialized sweep, killing weeds by smothering them. Repeated passes may be made. This technique is used for crops that can tolerate partial covering. Hilling is used for potatoes, com, leeks, asparagus, artichokes and other crops. Weed control is enhanced when weeds are no taller than 50 cm.

5 Conclusion

Before the advent of herbicides, mechanical methods of weed control were used successfully for several centuries. Cultivator technology continued to evolve even after the development of herbicides, and these implements are efficient and versatile. In some cases, they are the only weed control tools available and they are often a cost-effective alternative to herbicides.
Cultivators are agricultural implements that require careful adjustment to ensure optimal performance. To kill a maximum number of weeds, cultivators should be operated as close to crop rows as possible without injuring the crop. The effective use of cultivators requires a fair amount of experience and careful observation, which may explain why research teams arrive at widely varying conclusions in similar situations.
The effectiveness of cultivation is directly influenced by cultivation depth and degree of soil moisture. Cultivation that is too shallow may spare weeds and cultivation that is too deep increases the risk of crop damage. Working depth can be adjusted by means of wheels attached to the frame or the three-point hitch. The use of weights and reduction of tractor speed can also increase the operating depth. Cultivating when the soil is too wet leads to clod formation and may not destroy weeds. The optimal level of soil moisture depends on the cultivator type, with rotary hoes and harrows being best suited to moist soils.
In general, two types of cultivators are required for effective weed control: one at pre-emergence or early post-emergence and a second later in the season. The vulnerability of crops to damage depends on their growth stage. For example, legumes are most vulnerable at the hook stage, when cultivation can reduce yield. In Quebec, two to seven cultivations are usually carried out, depending on the crop and the degree of weed infestation. Tractor speeds range from 3 to 20 km h^{-1} depending on the cultivator type and the growth stage of (he crop.

Cultivation is not only effective in controlling weeds; it also benefits the crop by breaking up the surface crust, aerating the soil, stimulating the activity of soil microflora, reducing the evaporation of soil moisture and facilitating the infiltration of rainwater.

Cultivator selection is only one component of an effective weed control program. Technical mastery of the cultivator is critical, as is weeding at the appropriate growth stage of the weeds and the crop. Delaying treatment for a few days may significantly reduce the effectiveness of a cultivation operation. The timing of treatment is probably more critical in successful weed control than the choice of cultivator.

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Mechanical Weed Control in Corn *(Zea mays* L.)

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1 Introduction

Mechanical weed control in corn was practised as early as the 19th century. Over the past 30 years, however, effective selective herbicides have more or less replaced mechanical cultivation (Lampkin 1990). Although cultivation, or tillage, is still done because of the benefits to the soil, weed control is performed through an early-season application of herbicide. Tillage not only controls weeds but loosens the soil and breaks the surface crust, a common problem in corn growing. Crusts tend to form in silty clay soils after a period of rain followed by hot, windy weather. The crust slows oxygen diffusion and reduces heat transfer, makes emergence difficult for corn seedlings, and has a negative impact on crop uniformity. Removing the surface crust by cultivation also promotes mineralization of the nutrients required by corn (Souty and Rode 1994). In addition, cultivation helps to preserve soil moisture needed for plant growth, since the layer of loosened soil limits the capillary rise of moisture. This function of cultivation is most effective in regions with a dry climate and when the corn root system is not very well developed. When the roots are well distributed throughout the soil or the foliage provides shade, little moisture is lost even if the field has not been cultivated.

The exclusively mechanical weed control strategy explained here requires two types of treatments: an early pass over the entire field (broadcast cultivation), followed by a later pass between the crop rows (inter-row cultivation).

2 Broadcast Cultivation

The main problem in using cultivation for weed control in corn is removing the weeds from the crop row. Farmers have traditionally avoided passing over the rows, for fear of causing irreversible damage to the corn plants and seeing their yields decline. Today, tools are available that are kinder to crops. They pull out the weeds while they are still at an early stage of growth and have relatively poor root systems, but do little damage to the corn plants whose root systems are better developed. These implements can he pulled at a speed at least twice as fast as conventional cultivators and are generally used at the pre-emergence or early post-emergence stage.

Box 1. How Does Cultivation Destroy Weeds?
C. LaHovary

Cultivation can pull up, cut or bury a seedling. Although both dicots and monocots can be killed by pulling them up, only dicots can be easily destroyed just by cutting. Grasses (monocots) are more difficult to control by cutting than dicots because their meristem is protected by the sheath and remains intact when cut. However, as monocot growth nears the shooting stage, the meristem is increasingly exposed and vulnerable. Burying or smothering weeds is an effective complement to cutting or pulling them out, particularly when weeds are young. Dicots can be controlled by burial alone with 50% success, whereas grasses are more difficult to bury because of their upright growth habit. If the soil becomes wet after burial, this will benefit the weed since the seedling that has been pulled out will take root and begin to grow again. Furthermore, abundant rainfall reduces the effectiveness of burial by scattering the soil. Pulling up seedlings seems to be the best way of controlling weeds since it breaks the soil-root bond. Cutting slows growth but may leave meristem areas intact, particularly in grasses. One of the most important elements in cultivation is burial of seedlings, whether they have been pulled up or cut. Pulling up followed by burial is the optimum method of destroying weeds mechanically.

2.1 Cultivation Tools Used

The rotary hoe (Cloutier and Leblanc, Chap. 13} is used at depths between 2 and 5 cm, depending on the soil type and moisture conditions. Weights can he added to improve soil penetration when the crust offers excessive resistance. As the tractor moves forward, it drags the spiked wheels along with it, making them turn. The minimum speed required for effective weeding, is 10 km h^{-1}, although speeds of 20 km h^{-1} are common in the field. A wide variety of models are available on the market, including high ground clearance models for fields with considerable residues.

Harrows (rigid-tine and flex-tine) are more aggressive than the rotary hoe. The tractor speed used depends on the growth stage of the crop. In pre-emergence crops, the harrow can be operated at speeds of up to 15 km h^{-1}, compared with half this speed in a post-emergence situation. Reducing the tension on the tines allows faster cultivation. Several test runs are required to adjust the implement properly so as to prevent crop damage and control the weeds effectively. There is no need to work the soil at depths greater than 5 cm. This type of harrow does not work well in residues.

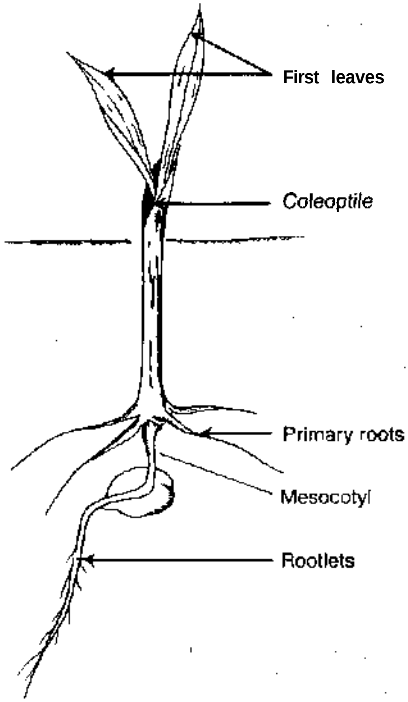

Fig. 1. Corn seedling.

2.2 Damage to Crop

Pre-emergence cultivation can be done faster and more aggressively than post-emergence cultivation, without harming the crop. The ideal time is roughly 24 h before emergence. Com takes roughly a week to come up, but this period can be longer or shorter depending on the region and climatic conditions. Emergence can also be deliberately prolonged by seeding at a greater depth, providing farmers with greater leeway for synchronizing cultivation with weed seed germination. Planting at depths of 5 cm or more may, however, reduce seedling vigor.

In com, the establishment of the seminal root system, formation of the mesocotyl (first internode) and tillering node and the elongation of the mesocoty] and coleoptile occur between germination and emergence (Fig. 1). The coleoptile, a sheath enclosing the young leaves, is pushed upward by the elongation of the mesocotyl until its base reaches the soil surface. There, inhibited by light, its edges spread apart at the tip, releasing the first foliage leaf. The length of the coleoptile is generally invariable in a given variety, while the length of the mesocotyl depends on the depth of planting, ranging from very short to up ten centimetres in the case of a deeply planted seed (Gay 1984). When the seed is too deep, the plant expends most of its reserves in producing the mesocotyl and therefore emerges in a much weakened state.

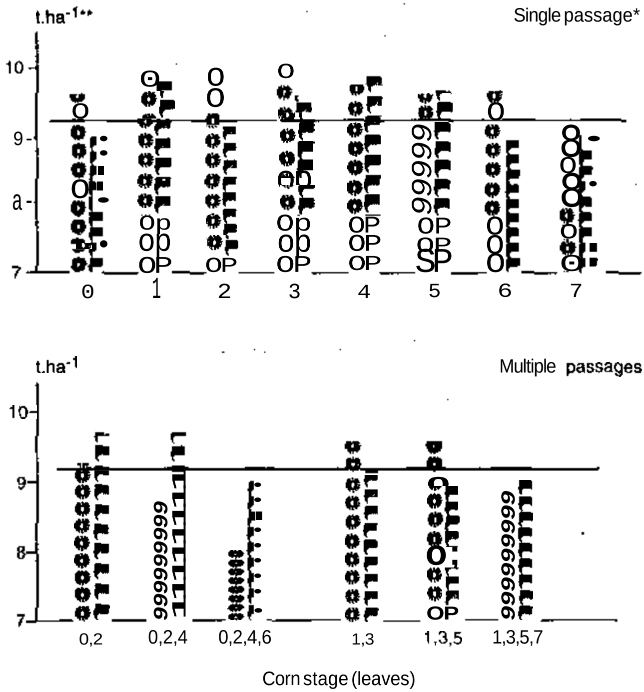

Fig. 2. Results of a 1994-95 study in Quebec to determine potential damage to different stages of com from single and multiple passes of a rotary hoe and rigid-line harrow. Soil types: clay and sandy loams; cultivators: Yetler rotary hoe and RaheWerk rigid-tine harrow (tines at low tension); tillage depth: 4 cm; speed: 15-18 km h^{-1}.
* In order to study the effect of weeders only and to avoid confounding their physical effects with the competing effects of weeds on corn yield, herbicides were applied on all surfaces (1 kg ha^{-1} atrazine, 1.9 kg ha^{-1} metolachlor). ** Field corn yield at 15% humidity.

After emergence, broadcast cultivation options are more limited. Both harrows and hoes have little negative impact on yield, provided they are used before the six-leaf stage no more than three times a season (Fig. 2). Rigid-tine harrows are generally more aggressive than hoes, usually bending down the corn as they pass over it (the plants are flexible, however, and will spring back after a few days). Around the end of the seven-leaf stage, cultivation is risky because the apex is al the soil surface and the tassel has begun to develop (Gay 1984). Any damage at this stage channels resources to the foliage and roots for repair purposes, resulting in decreased resources for cob production.

2.3 Effectiveness in Weed Control

Table 1. Relationship between growth stage of *Chenopodium album* L. and effectiveness of weed control using a rolary hoe (Douville et al. 1995).

Stage	Control (%)
Cotyledon	90-100
2-leaf	65
4-leaf	35

The younger the weeds, the more effective cultivation is. The best time for cultivation is when weed seeds have germinated but have not yet emerged. (To determine if this has occurred, take a handful of soil and examine the weed seeds to see if they have begun to sprout.) The young shoot is fragile and easily destroyed by the teeth of the hoe or harrow. Once weeds have emerged, cultivation should be done immediately since, according to recent studies, the effectiveness of tillage decreases rapidly as weed seedlings develop, becoming almost nil when weeds reach the three-to four-leaf stage (Table 1). Rotary hoes are excellent for controlling weeds at the cotyledon stage, while flex-tine and rigid-tine harrows, which are slightly more aggressive, are effective until the one-leaf stage (Douville et al. 1995). As the season progresses, all these implements become less effective, since the weeds are better rooted. Therefore, cultivation regime cannot be based strictly on calendar date, and the growth stage of the weeds must be taken into account in deciding when to cultivate. Some weed species (e.g. *Ambrosia artemisiifolia* L.) are more vigorous and establish root systems more quickly than others; hence, they must be treated at an earlier stage of growth. Other species germinate at greater soil depths (e.g. *Avena fatua* L.) and are more difficult to destroy with a rotary hoe or harrow. Readers should also note that rotary hoes and harrows are not effective in controlling perennial weeds.

3 Inter-Row Cultivation

When com has reached a certain height, a second type of cultivator is used strictly in the inter-row area, generally a goosefool sweep or a Danish S-tine. Inter-row cultivation on its own controls weeds mainly between the rows and there is very little control in the crop row, allowing weed populations to take over and compete with the crop. However, when combined with an early broadcast treatment using a rotary hoe or a rigid-tine or flex-tine harrow, inter-row cultivation allows weed control to be extended later in the season. It can also be used to supplement band application of herbicides (Leblanc et al. 1995). Cultivation must be done on the same number of rows that were seeded in one pass, since adjacent seeder passes might result in divergent or convergent rows. (If not, the accuracy of cultivation will be reduced since it will be necessary to cultivate farther from the row to avoid damage to the crop.)

3.1 Cultivation Tools Used

Several models of inter-row cultivators arc available on the market. The operating principle of these devices is very simple: cut, pull out and bury. The tools come in various shapes which reinforce these actions, providing more effective weeding. Inter-row cultivators are commonly divided into light and heavy cultivators.

3.1.1 Light Cultivators

Most farmers are familiar with these implements and their operating principles, adjusting and modifying them to suit their needs. Light cultivators, operated at speeds of 5 km h^{-1} on average, generally consist of a tool bar to which different types of tines or shanks can be attached. The shape of the tools selected depends on soil type and the treatment to be performed. Some models allow the working depth to be adjusted by means of a simple lever. Often, several rows of shanks are

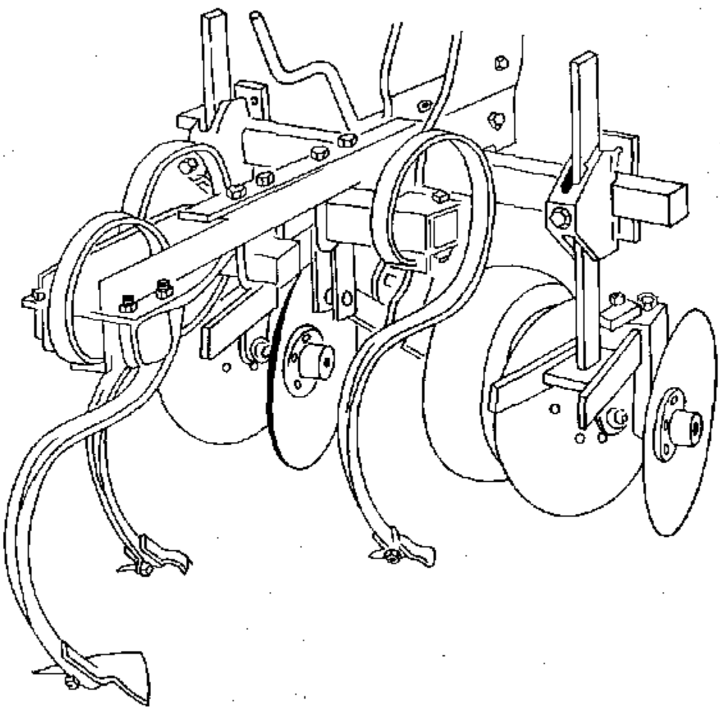

Fig. 3. Combination of Danish S-tines and disks.

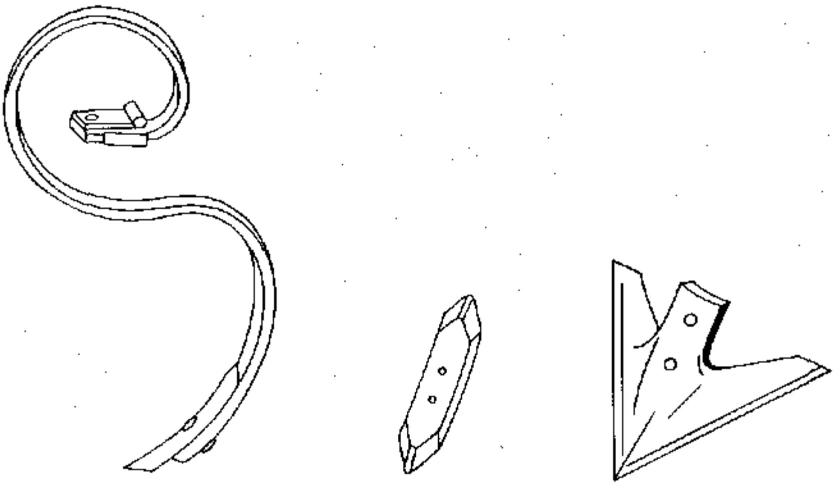

Fig. 4. A Danish S-tinc. **B Narrow** sweep. **C** Goosefoot **sweep.**

arranged in a triangle to provide coverage of the entire inter-row (Fig. 3). These cultivators offer good clearance beneath the tool bar (>50 cm), allowing them to be used on fairly tall crops. There are several types of rigid and vibrating shanks. To obtain maximum weeding intensity, shanks that can move in all directions are best. Danish tines (vibrating shank), which are shaped like an S, are the most widely used tool; they vibrate extensively and dislodge weeds from the soil effectively (Fig. 4). Various types of sweeps can be installed on the shanks. Goosefoot sweeps (25-45 cm) work along their entire width, loosening the soil and undercutting weeds by their roots. Narrow sweeps (6 cm), which stir up the soil, are used for deeper work. Disk hillers and rolling shields (Cloutier and Leblanc, Chap. 13) are also used for inter-row cultivation—sometimes in combination with shanks, sometimes alone (Fig. 3). These implements cut through the soil and are adjustable. Depending on their orientation to (he row, they throw the soil into the row or the inter-row.

3.1.2 Heavy Cultivators

Heavy cultivators, which are more recent, are mainly employed by corn growers using no-till or ridge-till production systems. The technology is designed to work with heavy crop residues. As their name implies, they are heavier, requiring 20 to 50% more tractor power for cultivation (St-Pierre 1993). These machines are also more expensive than light cultivators. However, they allow the work to be completed in the same amount of time. Several models of ridge-tillers are also available (some with only one goosefoot sweep per inter-row), in which ridging wings attached to the goosefoot sweeps carry out the ridging operation.

3.2 Damage to Crop

Inter-row cultivation is safe for crops as long as the goosefoot sweeps do not go too close to the corn rows or too far into the soil, which may cut the corn roots. Using cultivator shields is advisable when the corn is at the one- or two-leaf stage, to avoid damaging or smothering the young plants. The number of rows cultivated per pass must correspond to the number of rows seeded per pass, to ensure that the sweep does not destroy rows that are not exactly equidistant. Cultivation can be carried out until the corn has reached the ten-leaf stage (roughly 50 cm tall), or around 6 to 7 weeks after it emerges. However, late-season cultivation is not always beneficial since it may cause serious root system damage in corn. As early as a month after planting, the roots of the corn already extend into the middle of the inter-row, many in the first 4 cm from the soil surface (Mengel and Barber 1974). Fairly shallow cultivation is recommended. According to Weaver (1926), cultivating at a depth of 10 cm deep reduces the yield, whereas an operating depth of 4 cm will not. The first treatment in the season can he deeper to loosen the soil and allow it to dry and warm up, which also makes later cultivations easier. The optimum cultivation depth can be defined as that which is deep enough to kill weeds but shallow enough to minimize injury to corn roots. Earthing up (ridging up) during the last cultivation may also be beneficial, providing mechanical support to the corn stem and promoting the development of brace roots, which prevent stalk lodging during strong winds.

3.3 Effectiveness in Weed Control

Cultivators with goosefoot sweeps are much more aggressive than hoes or harrows, killing weeds at a more advanced stage of development (four to five-leaf stage). Due to their rapid growth, weeds can cover a field in a very short time, quickly reducing the chances of success of a weed control program. Cultivation depth can be adjusted, but going deeper than 5 cm deep is unnecessary since most weeds germinate at or near the surface. However, goosefoot sweeps can be used only for inter-row weeding. This allows weeds to enjoy uninterrupted growth in the row, where they can absorb fertilizer applied during seeding (indeed, weed biomass in the row may be 20 times higher than in the inter-row). Weed management can be greatly improved, therefore, by carrying out broadcast tillage early in the season. Later in the season, the cultivator shanks can be adjusted to throw the soil onto the row (ridging up) and thereby smother any late-germinating weeds that escaped preceding treatments. Late cultivation also prevents *inter-row* weeds from reaching maturity or from growing too tall. Ridge-tillers are much more aggressive than light cultivators and kill most weeds. Since they remove the top layer of soil and cut the weeds, their effectiveness is less influenced by the growth stage of the weeds.

4 Cultivation Conditions

Although cultivation for weed control in com can be carried out under a wide range of soil conditions, it appears to be less effective in very wet or very dry soils. According to Lovely et al. (1958), who evaluated several weed control methods, the presence of wet soil before or after cultivation significantly reduces its efficiency. Peters et al. (1959) demonstrated, however, that within certain limits, proper timing of cultivation in relation to weed emergence and weed growth stage has a greater effect on efficiency than does soil moisture. Cultivation is ineffective when the soil is so dry that it inhibits weed germination. Optimum conditions consist of lightly crusted soil and weeds that have germinated but have not yet emerged (Coleman 1954; Lovely et al. 1958; Peters et al. 1959; Rea 1955).

5 Cost-Effectiveness of Cultivation

According to an economic study done in Quebec, mechanical weed control is just as cost-effective as conventional chemical methods (St-Pierre 1993). A mechanical weed management program usually entails three or four passes a season. According to the study, the cost of four cultivations is less than that of one herbicide application (Table 2). The rotary hoe, although its cost falls in the mid-range, is the least expensive tool to operate per hectare because it can be used at high speeds. These findings are specific to the region where the study was carried out and cannot be generalized.

Table 2. Cost of weed control in Quebec in 1993.

Type of control	Average price (4.6 m swath)		Cost[a] ha^{-1} $pass^{-1}$	
	FF	($Can)	FF	($Can)
Rotary hoe	15 750	(3500)	31	(9)
Rigid-tine harrow	24 335	(6950)	55	(16)
Light cultivator	12 255	(3500)	45	(13)
Heavy cultivator	36 765	(10500)	82	(24)
Herbicides[b]			320	(91)

[a] Including labor.

[b] DUAL (metolachlor) + MARKSMAN (atrazine and dicamba). The cost of using the sprayer was estimated at $8 per ha (or 28 FF per ha).

6 Conclusion

Using two (ypes of cultivators in combination provides synergy by harnessing the best features of each one. The main problem farmers face is the wide variation in weed emergence times. Setting cultivation periods and the number of passes based on the calendar alone may result in ineffective or unnecessary cultivation. Instead, treatments must be based on the growth stage of the weeds. Risks of reduced yields increase when broadcast cultivation is done in corn beyond the six-leaf stage. Late cultivation is not always beneficial since it may result in significant root damage to corn. To sum up, growing corn without using herbicides is not only feasible but cost-effective. However, careful attention must be paid to the conditions under which cultivation is done (soil moisture, speed and depth of cultivation, type of soil, compaction). In short, timely treatments must be combined with the optimal use and adjustment of mechanical equipment.

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Mulching and Plasticulture

Serge Bégin, Sylvain L. Dubé and Joe Calandriello

1 Introduction

Although the main objective of plasticulture in horticultural crop production is to reach harvest earlier and improve productivity, mechanical control of pests is another, albeit less widespread, application. Two techniques are employed: mulches and floating row covers. Mulching involves covering the soil at the base of cultivated plants with a layer of protective material such as straw, thoroughly decomposed manure, peat moss, bark chips, sawdust, paper or plastic sheets. Floating row covering constitute a semiforcing technique using perforated plastic films that are spread over both the soil and plants (Gerst 1992).

Mulches smother weeds, conserve water, prevent the movement of salts to the soil surface, add organic materials to the topsoil and reduce leaching of fertilizer. The use of traditional plant fibre mulches to control weeds has largely been abandoned in favour of polyethylene, which is better suited to intensive farming. Polyethylene mulches have been used for mulching since the early 1950s (Lamont 1993).

The use of plastic mulches in fruit and vegetable production enhances productivity (Downes and Wooley 1966), fruit quality (Downes and Wooley 1966; Decoteau et al. 1990). root system development (Jones et al. 1977), and controls weeds effectively (Smith 1968). Plastic mulches appear to provide a good return on investment (Sanders et al. 1986). The beneficial effects of mulch can be attributed mainly to increased soil temperatures (Taber 1983; Begin et al. 1994), but also to water conservation (Jones et al. 1977), microclimate change (Sanders 1986) and reduced leaching of nutrients (Locascio 1985).

Plastic materials modify the spectrum of incident light, alter the temperature and serve as a physical barrier, all of which are useful for weed suppression. This chapter will examine the use of mulches and plasticulture for physical control of pests in horticultural crops.

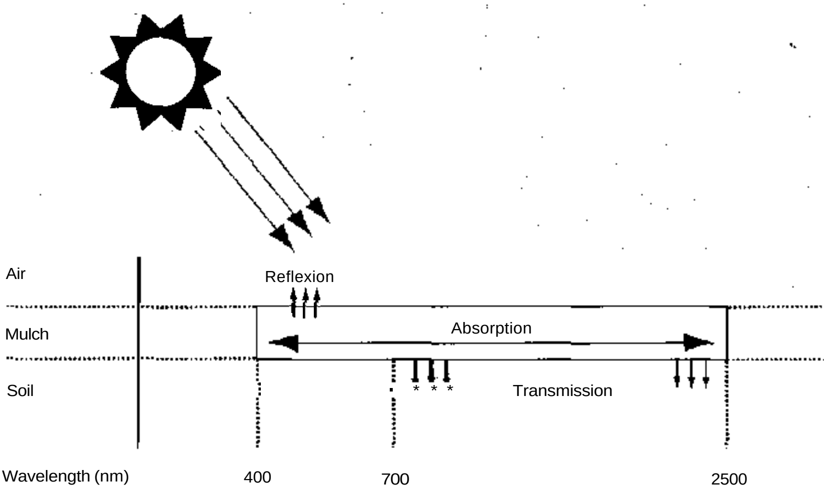
2 Wccd Control

2.1 Effects on Photosynthesis

Both black and clear polyethylene are used as mulch for horticultural crops. Black plastic controls weeds by blocking the light, and preventing their photosynthetic activity. Under clear plastic, weeds proliferate but are eventually crushed by the film or are killed by the high temperatures. Since weeds may grow through the openings intended for the crop, herbicides are still required. However, by limiting leaching, plastic mulches reduce the dose of herbicides needed to obtain an equivalent level of control (Brun 1992).

Photoselective mulches (Fig. 1), that combine the advantages of both black and clear films, have been available for a number of years. They control weed growth while accelerating soil wanning. For example, some photoselective plastic materials absorb or rellect photosynthetically active radiation (wavelengths of 400-700 nm), but transmit wavelengths between 700 and 2500 nm (Begin et al. 1995).

Opaque mulches made of cellulose fibre are effective for controlling weeds, although they may degrade quickly. Some materials currently being tested may provide similar yields to those obtained with plastic films on sweet corn and peppers.



Fig, 1. Behavior of ideal photoselective film at various wavelengths of incident solar radiation (400–2500 tun).

2.2 Photomorphogenesis

Light is the source of energy for many light-dependent phenomena that are independent of or complementary to photosynthesis. Some of these phenomena affect plants by modifying their growth or morphology (hence the name photomorphogenesis). Weed germination and growth can be hindered by covering weeds with materials that filter out certain wavelengths. In addition, by promoting the reflection of specific wavelengths, crop growth can be influenced.
Phytochrome is a wavelenght sensitive pigment that is often associated with photomorphogenesis. It is a photoreversible pigment that exhibit peak absorption in the near infrared (660 nm) and far-red (730 nm) ranges respectively (Fig. 2). Phytochrome is present in all green plants and is particularly abundant in buds, subapical zones, meristem and storage organs. The two forms of phytochrome are called Pr (red-absorbing phytochrome) and Pfr (far-red-absorbing phytochrome). Phytochrome is synthesized in its Pr form (Jose and Schafer 1978). The seeds of some weeds must be stimulated by near-infrared light to germinate, meaning that the Pfr form must be active. The active form (Pfr) returns to its inactive form (Pr) in a photoconversion reaction induced by the absorption of far-red wavelengths. In the dark, Pfr may revert spontaneously to Pr through enzymatic degradation. A photostationary state may occur when the proportion of Pfr to Pr is stable (the destruction of Pfr always equalling the production of Pfr) (Heller 1985).
When dicots or conifers grow under a canopy of other plants, they receive wavelengths that tend to be concentrated in the far-red band, causing the stems to become elongated or etiolated. Under these conditions, some species delay the development of lateral stems and channel their energy into height growth, in order to

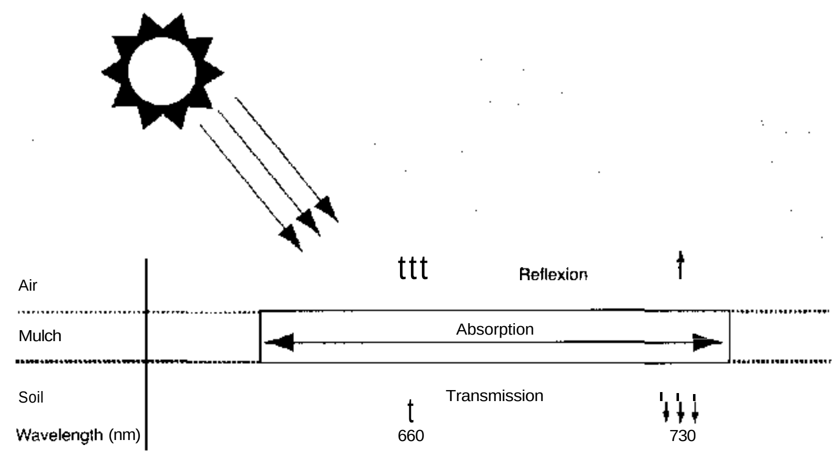


Fig. 2. Behavior of an ideal photoselective film for controlling wavelengths affecting morphogenesis.

bring the apex above the plant cover. This is typical of row crops, with the plants at the ends of the rows being shorter and stouter, with more lateral stems than the plants in the middle of the field.

Light quality can be quantified by the ratio of red to far-red (R/FR ratio), or the ratio of radiant flux measured in the 655–665 nm band to that measured in the 725-735 nm band (Smith 1982). Although the R/FR ratio of light reflected from white plastic mulch (1.00) and black plastic mulch (0.94) is very similar, according to Anderson et al. (1985), the difference is significant enough to affect the height of tobacco plants in the field, indicating that the use of black mulch is preferable in tobacco.

According to Decoteau et al. (1988), the differences in yield found between tomatoes produced with white plastic mulch and black plastic mulch can be attributed to the greater proportion of radiant flux in the blue band (400 nm) reflected by white mulch. This plays a role in regulating the growth of tomatoes, causing them to have shorter stems and increased growth in axillary stems (Tanada 1984). A similar tendency has been found in soybeans and peppers: plants that receive reflected light with a low R/FR ratio (<1) from red or black mulch exhibit 51% more elongation than plants that are exposed to reflected light from white or yellow mulch (Decoteau et al. 1990). The latter mulches produce reflected light with a higher R/FR ratio (>1) and reflects more light in the 400–700 nm hand. Photoselective materials for weed control should therefore favour wavelengths that do not promote weed growth but favour heat accumulation in the rhizosphere. Additional objectives should be the promotion of optimal photosynthetic activity in the crop above the mulch and optimal control of photo morphogenesis to enhance growth and development.

3 Controlling Insects with Colour

The high reflectance of aluminized films deters some insects and can be an effective method of physical pest control. Insects ability to locate their host plants is impaired by the reflected light, although the repellent properties of the film decrease as the crop grows and covers the exposed plastic surfaces. Highly reflective sheeting and mulches help to prevent insect invasions and reduce crop damage.

In tomato and squash production, reflective materials have been found to repel some insects but attract others (Wolfenbarger et al. 1968). Bees, important pollinators, are attracted by aluminized material (Schalk et al. 1979). Thrips are attracted by blue (Csizinszky et al. 1990) and black and white (Brown 1989); aphids by yellow (Black 1980) and blue (Csizinszky et al. 1990); and whitefly by red (Csizinszky et al. 1990). The tomato fruitworm (*Heliothis zea*) and tomato pinworm (*Keiferia lycopersicella*) are attracted by reflective or aluminized materials (Schalk et al. 1987). In contrast, some species of leafminers (Wolfenbarger et al. 1968) and aphids (Schalk et al. 1987) are repelled and disoriented by these materials, which also slow the transmission of viruses in squash and watermelon (Black 1980) and lettuce (Nawrocka et al. 1975) and hinder the development of whitefly eggs and nymphs on broccoli (Chu et al. 1994).

The repellent properties of aluminized mulches are probably due to the increased reflection of light, particularly in the ultraviolet band at wavelengths less than 390 nm (Kring and Schuster 1992). Although white mulches emit a similar radiant flux in the visible wavelengths, they emit very little in the ultraviolet range. The density of the aluminium pigments used is crucial in controlling aphids (Wolfenbarger et al. 1968), and at least 50% of the soil surface must be reflective to repel insects (Garnaud 1992).

4 Controlling Diseases with Colour

Light requirements for sporulation in fungi often vary with environmental conditions and with particular species. Ultraviolet light affects sporulation in many pathogenic fungi. Continuous diffused light and total darkness also inhibit sporulation.

Blue light induces sporulation in *Trichoderma viride* and *Verticillium agaricinum*, but inhibits it in *Alternaria tomato, A. cichorii* and *Helminthosporium oryzae*. In the case of *Botrytis cinerea* Pers. ex Fr., UV-B (280-320 nm) induces sporulation, while blue light inhibits it (Reuveni et al. 1989).

Fungal diseases caused by *Botrytis, Sclerotinia, Alternaria* and *Stemphyllium* can be controlled by using UV-absorbing vinyl films as a greenhouse cover. Grey mould is effectively controlled by using photoselective films (Reuveni et al. 1989). A high ratio of blue light to ultraviolet light is required to prevent sporulation and a high radiant flux of blue light is required to provide long-term inhibition. Inhibition of sporulation in *B. cinerea* by blue light is initiated by the conversion of a sporulation-promoting form of mycochrome to a sporulation-inhibiting form (Tan 1974).

5 Controlling Crop Pests with High Temperatures

The solari/.ation or sterilization of soil with plastic row covers or mulches is a promising alternative to chemical disinfectants. This process involves covering moist soil for several weeks with clear plastic. Through the greenhouse effect, heat builds up under the plastic, increasing the soil temperature to a level that significantly decreases populations of harmful organisms. Although numerous studies have been carried out on this form of physical control for various crops and pathogens at southern latitudes (Martin 1992), more recent experiments show that this technique also has potential at northerly latitudes. Most harmful soil microorganisms are more sensitive to temperatures around 40 °C than useful soil microorganisms. Thus, maintaining the soil temperature at 40 °C or above for an extended period of time eliminates most fungi, bacteria, weed seeds and nematodes.

Some strains of *Verticillium dahliae* are controlled after less than 30 min of exposure to temperatures of 50 °C. At 37 °C, exposure for *26* to 29 days is required to

Table 1. Plant diseases controlled by solarization.

Common name	Scientific name
Seedling blight	*Rhizoctonia* and *Pythiacees*
Wilt	*Fusarium* and *Verticillium*
Tomato corky root rot	*Pyrenochaeta lycopersici*
Clubroot	*Plasmodiophora brassicae*
Soil-borne fungi	*Sclerotinia minor* and *S. rolfsii*

obtain the same result (Pullman et al. 1981). The effectiveness of solarization depends on the soil temperature, length of exposure (Martin 1992) and the depth of soil heating (Lopez-Herrera et al. 1994). A solarization period of 6 or 10 days is required to eradicate the sclerotia of *Botrytis cinerea* at depths of 15 and 25 cm respectively. Total eradication of *Verticillium dahliae* is achieved when soil is solarized to a depth of 25 cm, while only 63% control of *Fusarium oxysporum* is achieved at the same depth (Katan et al. 1976).

Using a polyethylene covering on the soil affects soil microflora by promoting anaerobic activity, leading to increases in populations of pectinolytic bacteria among other things (Stapelton and deVay 1984). Solarization increases the volatile ammonia concentration (two to five times) and organic sulphur compounds in the soil. These two volatile compounds have fungistatic effects on fusarium rot and fungicidal effects on pea root rot. Studies suggest that soil amendments promoting the release of these volatiles should be used in conjunction with impermeable films. This also promotes the growth of populations of antagonists, which have better heat tolerance. For example, *Trichoderma* spp. have been found to reduce the virulence of *Fusarium* spp. (Foury 1995). Sublethal temperatures are also useful, since they weaken pathogens and make them more susceptible to their natural enemies.

Stevens (1989a) reported more than 90% weed control for 10 months after solarization using a preplant treatment with plastic mulch. This author also observed an appreciable decrease in nematodes (Stevens 1989b). Solarization also allows the control of some economically important diseases (Table 1).

6 Controlling Crop Pests with Physical Barriers

6.1 Floating row cover

Floating row covers are being used increasingly to provide mechanical crop protection. In Europe, over 16 500 ha of vegetables are grown under these covers (Thicoipe 1992). Unwoven sheets of polyamide, polyethylene, polyester or polypropylene are laid directly over the crop or installed on stand wires, forming a barricr for insects. Floating row covers arc mainly used for high valuc-added crops such as peppers, tomatoes and cucurbits. They control cabbage maggot and carrot fly just as well as chemical insecticides. They are also effective against flea beetles, flies and potato beetles (Gerst 1992) as well as cabbage maggot on broccoli (Purser 1990). In addition, row covers provide an effective barrier against virus transmission by aphids (Gomez 1989). Mesh size must be taken into account. For example, 300-µm mesh is required to control thrips, while 500-µm is required for aphids. Plastic floating row covering are considered to be more environmentally friendly than many pesticides (South 1991). It also holds promise for the production of virus-free potatoe seeds (Hemphill 1988).

6.2 Mulch

The use of black plastic mulch in orchard crops has been found to reduce the population of one species of nematodc (*Pratylenchus hamatus*), but increase the numbers of another species (*Meloidogyne incognita*) (Duncan et al. 1994). The latter pest probably tolerates higher temperatures better and is able to continue its development. Plastic mulch may also be used as a barrier against leafminer larvae, preventing them from reaching the plants to pupate (Chalfanl et al. 1977).
Mulching the soil with plastic creates a physical barrier that hinders the transmission of some soil pathogens to the foliage, such as *Sclerotium rolfsii* in peppers (Garnaud 1992). Generally, when combined with soil sterilization, plastic mulch significantly reduces disease caused by soil fungi such as *Fusarium*, *Pseudomonas*, *Phoma*, *Verticillium*, *Sclerotinia*, *Alternaria* and *Pythium*. In France, mulch-grown shallots have been very successful due mainly to the fungicidal effect of plastic film on white rot (*Sclerotium cepivorum*). The use of black plastic mulch and sheeting reduces the incidence of early blight of tomato (*Alternaria solani*), although not as effectively as fungicides (Stevens et al. 1993). *Pythium* (*Pythium* spp.) is a major problem in tomato crops when the fruits lie on the ground. Fungal diseases in fruit arc also caused by other fungi such as *Phytophthora* and *Rhizoctonia solani*. Polycthylene film prevents rot, serving as a physical barrier to infection (Duncan 1993).

7 Conclusion

Plasticulture can be successfully incorporated into integrated pest management programs and organic farming methods, while we await the revolutionary changes promised by proponents of biotechnology. Plasticulture could be of importance for high value-added crops, particularly in cold climates. The problem of disposing of the plastic afterwards has not been resolved, however. Fanners have two choices: developing a cost-effective system with obligatory recycling or lobbying manufacturers to produce photoselective plastic materials that are photobiodegradable.

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