Chapter 8
Integrated Weed Management in Maize

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Introduction

Maize (*Zea mays* L.), also known as corn in the Americas, is one of the most important cereal crops. Corn belongs to the grass family Poaceae and tribe Maydeae. Among other cereals, corn has the highest genetic yield potential; therefore, it is known as "queen of cereals." Flint, dent, floury, sweet or sugary, popcorn, multicolored, and other types of corn are grown throughout the world, with color, size, kernel shape, and other attributes varying significantly. The production of yellow corn predominates in the USA, Brazil, and China. However, white corn is preferred in Africa, Central America, and the northern part of South America [1]. Using climatic data where corn is most productive, Harshberger reported that corn originated in Mexico and had once been a wild plant in central Mexico [2]. A closely related species of corn, teosinte, and the landrace diversity of corn have been found on

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the central plateau and western escarpment of Mexico–Guatemala that supports the theory of origin of corn in this region.

Corn is the most versatile crop with wider adaptability to varied agroecological regions and diverse growing seasons. Besides serving as human food and animal feed, the importance of this crop also lies in its wide industrial applications. For example, corn oil is used in margarine, corn syrup sweeteners in marmalade, and corn syrup solids in instant non-dairy coffee creamer. In addition, corn is fed to cows, chickens, and pigs, which produce milk, eggs, and bacon, respectively. Furthermore, corn finds application in a candy bar, a beer or bourbon whisky, a hamburger, industrial chemicals, ethanol in gasoline, plastics, and in the paper sizing of a glossy magazine [3]. Responding to its multiple uses, the demand for corn is constantly increasing in the global market. New production technologies, such as improved hybrid cultivars, precision agriculture, herbicide-resistant traits, and biotechnological innovations, such as drought-tolerant corn, offer great promise for increasing corn productivity to meet the growing demand.

Globally, corn is grown on more than 175 million ha across 166 countries with a production of around 880 million t [4]. The global output of corn in 2013 was forecast at about 963 million t, 10 % up from 2012 [4]. The top six corn-producing countries are the USA, China, Brazil, India, Mexico, and Argentina. The USA is producing about 30 % of the total corn produced in the world. In addition, the USA is the largest exporter of corn to several destinations in the world. In 2013, it was expected that corn production in the USA would reach about 340 million t [4].

Excluding environmental variables, yield losses in corn are caused mainly by competition with weeds. Weed interference is a severe problem in corn, especially in the early part of the growing season, due to slow early growth rate and wide row spacing. Weeds compete with the corn plants for resources such as light, nutrients, space, and moisture that influence the morphology and phenology of crop, reduce the yield, make harvesting difficult, and mar the quality of grains. Furthermore, high weed infestation increases the cost of cultivation, lowers value of land, and reduces the returns of corn producers. In order to realize the yield potential of corn, weed management becomes indispensable. Weed species infesting the corn crop are functions of a complex interaction among soil characteristics, climate, and cultural practices. These factors vary across regions and influence the composition and number of predominant weeds of economic importance to corn production [5].

The critical period of crop–weed competition and weed threshold are two important aspects in a weed management program in any crop. The critical period may be defined as the time period after crop emergence during which crop must be kept weed-free to prevent yield losses, described as losses greater than 5 % in earlier studies [6, 7]. Likewise, weed threshold, defined as the weed density above an acceptable count, provides an opportunity to decide the right time to take appropriate control measures to avoid yield loss [8, 9]. Weeds that emerge at the time of crop germination or within a few days of crop emergence cause greater yield loss than weeds emerging later in the growing season [8, 10, 11]. The critical period is useful in defining the crop growth stages most vulnerable to weed competition. The critical period of weed control in corn ranges from 1 to 8 weeks after the crop emergence [12–14]; however, to avoid limitations associated with critical period for weed control (CPWC) like weed-species specificity and inconsistency across climate and locations, the onset of critical period for crop weed control is reported to occur on an average between the first (V1) and the third (V3) leaf stages of development [15], while the end of critical period typically coincides with the V8–V10 stages, which is the time of canopy closure in 76-cm row spacing [16–20].

A number of weed species compete with corn plant (Table 8.1) and have been observed to reduce yield as much as 65 % with delay in weed control [15]. Some of the weeds in corn are difficult to control, known as problem weeds, because they have similar life cycle and growth habits as those of the corn plant. Weed species, densities, and their interactions influence corn yield loss [21, 22]. Massing et al. reported yield reduction in corn as much as 91 % by competition with eight Palmer amaranth (*Amaranthus palmeri* S. Wats) plants per meter row length [23].

Corn-based cropping systems in the USA are heavily dependent on herbicide-resistant corn hybrids (e.g., glyphosate-, glufosinate-, or imidazolinone-resistant corn). These crop production systems rely heavily on the use of postemergence herbicides, such as glyphosate, as glyphosate-resistant hybrids dominate the market. Repeated use and solely relying on glyphosate for weed control resulted in an increasing number of herbicide-resistant weeds, shifts in weed species population, higher cost of chemical control measures, and leaching of herbicide into groundwater and surface water as well as herbicide residues in drinking water and food, which have sparked public awareness and restrictions on herbicide use [24–26]. Herbicides have often been cited as one of the main factors responsible for causing a general impoverishment of the flora and fauna in the agricultural landscape [27, 28]. To address these challenges, many countries have developed policies that mandate the reduction of herbicide use and provide incentives to producers for reducing overall chemical use [29–31].

Integrated Weed Management in Corn

Integrated weed management (IWM) has been defined as a multidisciplinary approach to weed control, utilizing the application of numerous alternative control measures [32]. The IWM involves a combination of cultural, mechanical, biological, genetic, and chemical methods for an effective and economical weed control that reduces weed interference with the crop while maintaining acceptable crop yields [18, 33]. None of the individual control measures can provide complete weed control. However, if various components of IWM are implemented in a systematic manner, significant advances in weed control technology can be achieved [32].

The IWM approach advocates the use of all available weed control options that include:

1. Selection of a well-adapted crop variety or hybrid with good early-season vigor and appropriate disease and pest resistance

Table 8.1 Major weeds of corn in the USA listed by family name, scientific name, and life cycle. (Reprinted with permission from Kremer [5])

Family/common name	Scientific name	Life cycle
Monocots		
Cyperaceae		
Purple nutsedge	*Cyperus rotundus* L.	Perennial
Yellow nutsedge	*C. esculentus* L.	Perennial
Poaceae		
Barnyardgrass	*Echinochloa crus-galli* (L.) Beauv.	Annual
Bermudagrass	*Cynodon dactylon* (L.) Pers.	Perennial
Broadleaf signalgrass	*Brachiaria platyphylla* (Griseb.) Nash.	Annual
Crabgrass	*Digitaria* spp.	Annual
Fall panicum	*Panicum dichotomiflorum* Michaux.	Annual
Field sandbur	*Cenchurus incertus* M.A. Curtis	Annual
Foxtails	*Setaria* spp.	Annual
Goose grass	*Eleusine indica* (L.) Gaertn.	Annual
Johnsongrass	*Sorghum halepense* (L.) Pers.	Perennial
Quack grass	*Elytrigia repens (*L.) Nevski	Perennial
Red/weedy rice	*Oryza sativa* L.	Annual
Shattercane	*Sorghum bicolor* (L.) Moench	Annual
Wild proso millet	*Panicum miliaceum*	Annual
Wooly cupgrass	*Eriochloa villosa* (Thunb)Kunth	Annual
Dicots		
Amaranthaceae		
Common waterhemp	*Amaranthus rudis* Sauer	Annual
Palmer amaranth	*A. palmeri* S. Wats.	Annual
Powell amaranth	*A. powellii* S. Wats.	Annual
Redroot pigweed	*A. retroflexus* L.	Annual
Smooth pigweed	*A. hybridus* L.	Annual
Spiny pigweed	*A. spinosus* L.	Annual
Tall waterhemp	*A. tuberculatus* (Moq.) Sauer	Annual
Apocynaceae		
Hemp dogbane	*Apocynum cannabinum* L.	Perennial
Asclepiadaceae		
Common milkweed	*Asclepias syriaca* L.	Perennial
Honeyvine milkweed	*A. albidus* (Nutt.) Britt.	Perennial
Asteraceae		
Canada thistle	*Cirsium arvense* (L.) Scop.	Perennial
Common cocklebur	*Xanthium strumarium* L.	Annual
Common ragweed	*Ambrosia artemisiifolia* L.	Annual
Giant ragweed	*A. trifida* L.	Annual
Horseweed	*Conyza canadensis* (L.) Cronq.	Annual
Jerusalem artichoke	*Helianthus tuberosus* L.	Annual/biennial
Wild lettuce	*Lactuca* spp.	Annual
Wild sunflower	*Helianthus annuus* L.	Annual
Brassicaceae		
Wild mustard	*Brassica* spp.	Annual

Table 8.1 (continued)

Family/common name	Scientific name	Life cycle
Chenopodiaceae		
Common lambsquarters	*Chenopodium album* L.	Annual
Kochia	*Kochia scoparia* (L.) Roth.	Annual
Russian thistle	*Salsola iberica* Sennen and Pau	Annual
Convolvulaceae		
Field bindweed	*Convolvulus arvensis* L.	Perennial
Morning glories	*Ipomoea* spp.	Annual
Cucurbitaceae		
Burcucumber	*Sicyos angulatus* L.	Annual
Malvaceae		
Prickly sida	*Sida spinosa* L.	Annual
Spurred anoda	*Anoda cristata* (L.) Schlecht.	Annual
Velvetleaf	*Abutilon theophrasti* Medik.	Annual
Polygonaceae		
Curly dock	*Rumex crispus* L.	Perennial
Pennsylvania smartweed	*Polygonum pensylvanicum* L.	Annual
Wild buckwheat	*P. convolvulus* L.	Annual
Portulacaceae		
Common purslane	*Portulaca oleracea* L.	Annual
Solanaceae		
Eastern black nightshade	*Solanum ptycanthum* Dun.	Annual
Horsenettle	*S. carolinense* L.	Perennial
Groundcherry	*Physalis* spp.	Perennial
Jimsonweed	*Datura stramonium* L.	Annual

2. Appropriate planting patterns/spacing and optimal plant density, improved timing, placement, and amount of nutrient application
3. Appropriate crop rotation, tillage practices, and cover crops
4. Suitable choice of mechanical, biological, and chemical weed control methods
5. Alternative weed control tools (flaming, steaming, infrared radiation, sand blasting, etc.)

Cultural Control

Cultural practices play an important role in weed management program in corn. Corn is a very competitive crop; so if managed properly, it provides considerable competition against weeds. Research has shown that weeds that emerge after 4 weeks of corn establishment have less impact on corn yield [8, 18]; therefore, early-season weed control is extremely important to get a competitive corn yield. It is important to establish a uniform plant stand at desired density. Soil tilth, fertility, pH, and drainage must be suitable for the crop to be competitive with weeds. As much as possible, the crop must be managed to minimize stresses on the crop from insect and disease damages and environmental stresses (frost, flooding, drought, etc.). Row spacing is an important cultural practice affecting weed control because corn in narrow rows will shade soil surface earlier than corn in wider rows. Once the canopy has closed, very little light reaches the soil surface or weeds beneath the canopy. The value of early canopy closure for weed control is especially evident when weed control program in corn is dependent on postemergence herbicides only.

Historically, crop rotation has been one of the most common methods of managing weeds. The more diverse the crop in rotation in planting time, growth habit, and life cycle, the more effective the rotation will be in controlling weeds. Thus, the selection of a crop in rotation that includes small grains, forages, and legumes is significant; however, such crops are no longer widely grown in the North Central USA. While modern rotations tend to include shorter cycles and fewer crops, a 2-year corn–soybean (*Glycine max* [L.] Merr.) rotation, especially if it includes a different tillage system for each crop, can help to manage some weeds. As in any rotation used over many years on the same field, certain weeds will often adapt to the rotation and become problem weeds or evolve resistance to herbicides over time.

Use of cover crops is another example of cultural control of weeds. Cover crops can be used for a variety of purposes including protecting the soil against erosion, improving soil structure, fixing nitrogen, feeding the soil biological life, and managing soil moisture [34]. A key soil health concept is that there should be something green and growing during as much of the year as possible. Grasses provide the long-lasting residue cover because they have a higher carbon to nitrogen ratio in their biomass compared to non-grass species. In addition, they improve snow catch in the winter and reduce wind erosion in the spring compared to the bare soil. Taller brassicas with broad leaves like rape, mustards, and canola will also effectively reduce wind erosion and catch snowfall, but they provide less residue. In conclusion, a healthy, vigorous corn crop with a high yield potential will be very competitive with weeds; however, competition from the crop alone is not sufficient to provide a season-long weed control. Other methods of control must be used in conjunction with cultural control measures.

Mechanical Weed Control

Tillage is the most common method of mechanical weed control and it can be divided into two categories: (1) preplant tillage and (2) in-row cultivation. The purpose of preplant tillage is to kill all the weeds present before planting corn to give the crop a better start to compete with weeds during the initial stage. Field cultivators and discs are commonly used by growers, and they are highly effective for controlling weed seedlings if used properly. The in-row cultivation is used to remove weeds after the crop has been planted, usually using rotary hoe or an inter-row cultivator. Rotary hoes are most effective on small-seeded broad-leaved weeds and grasses, but they are less effective on large-seeded broad-leaved weeds, such as giant ragweed, velvetleaf (*Abutilon theophrasti* Medik.), cocklebur (*Xanthium strumarium* L.), etc. Rotary hoes are usually operated at the speed of 13–19 km/h and should be used after planting the crop but before weeds have emerged or after weed germination. Another advantage of in-row cultivation is that they are useful when soil-applied herbicides fail to control weeds due to lack of rainfall. Several types of in-row cultivators are available in the market, but it is important to adjust the equipment to effectively kill as many weeds as possible in the interrow area while minimizing the disturbance of the crop plants.

Flame Weeding

Flaming controls weeds primarily by rupturing the cell membranes that leads to subsequent tissue desiccation [35]. Propane burners can generate combustion temperatures up to 1900 ℃, which raises the temperature of the exposed plant tissues rapidly [36]. An increase of temperature above 50 ℃ inside the plant cells can result in the coagulation (denaturation and aggregation) of membrane proteins leading to loss of the membrane integrity [35, 37, 38]. Consequently, flamed weeds would die or their competitive ability against the crop would be severely reduced. The susceptibility of plants to flame largely depends on their heat avoidance, heat tolerance, or both [39]. The extent to which heat from the flames penetrates plants depends on the flaming technique and leaf surface moisture [37]. The effects of flaming on plants are influenced by several factors including temperature, exposure time, and energy input [40]. Depending on the exposure time, protein denaturation may start at 45 ℃ [40]. Temperatures in the range of 95–100 ℃ at least for 0.1 s have been reported to be lethal for leaves and stems [40].

Heat from the flames has a direct effect on the cell membranes and an indirect effect on the subsequent tissue desiccation. Cellular death after flame treatment is primarily due to the initial thermal disruption of cellular membranes rapidly followed by dehydration of the affected tissue. Tissue dehydration occurs mainly due to expansion of the cell contents (made of up to 95 % water), subsequent bursting of the cell membranes, and coagulation of membrane proteins [41, 42].

The efficacy of flame weeding was reported to be influenced by several factors, including the presence of protective layers of hair or wax and lignification [39, 40], the physical location of the growing point at the time of flaming [39,43, 44], plant growth stages [39, 45–51], the regrowth potential of plant species [39, 40], the technique of flaming [37], and the relative leaf water content of plant species [52]. Ulloa et al. conducted a series of studies where the authors intentionally flamed several agronomic crops such as field corn, popcorn (*Z. mays* L. var. *everta*), and sweet corn (*Z. mays* L. var. *rugosa*) [48–51, 53, 54]. Response to broadcast flaming varied among corn types, their growth stages, and propane dose. Popcorn was the least tolerant while field corn was the most tolerant to broadcast flaming based on the maximum yield reduction obtained with the highest dose of propane (85 kg ha^{-1}).

Field corn flamed broadcast at the five-leaf stage (V5) was the most tolerant while the two-leaf stage (V2) was the most susceptible, which had the highest visual crop injury and the largest loss of yield and yield components [53]. Visual crop injury symptoms included initial whitening and then browning of leaves. Stunting of growth was especially evident when the plants were flamed with higher propane doses (44 and 85 kg ha^{-1}). Most visual crop injuries, however, were transient as corn plants appeared to be visually recovered within a few weeks [46, 47, 53].

Popcorn flamed at the V5 stage was the most tolerant while the V2 was the most susceptible stage for broadcast flaming [50]. Plants flamed at the V2 stage had the highest yield loss and the lowest yield components. This might be explained by the fact that the ear and tassel tissues are not differentiated at the V2 stage [55]; thus, exposing the plants to the stress from heat can result in potentially shorter cobs. In comparison, flaming popcorn plants at later growth stages (e.g., V5 or V7) had less effects on cob size as the ear and tassel tissues start to differentiate at the V5 stage, and by the V7 stage, cob and tassel sizes are already predetermined [55]. A propane dose of 60 kg ha^{-1} resulted in 8, 9, and 21 % yield reductions at the V5, V7, and V2 stages, respectively, which would not be acceptable by organic farmers. These yield reductions were the result of the intentional flaming where torches were positioned directly over the crop rows. However, positioning flames below the popcorn canopy would reduce the exposure time to the heat and, therefore, should reduce popcorn yield losses.

Sweet corn flamed at the V7 stage was the most tolerant while the V2 was the least tolerant stage for broadcast flaming [49]. Sweet corn flamed at the V7 stage had the least yield loss and the least affected yield components compared to plants flamed at the V5 and V2 stages. The V2 was the most sensitive stage for broadcast flaming, resulting in the highest yield loss and the largest effects on yield components. Among the yield components, number of plants per square meter and seeds per cob were the most affected parameters when flaming was conducted at the V2 and V5 stages. Sweet corn generally starts to accelerate its growth around the V6–V7 stages (growing point reaches soil surface). This growth acceleration in sweet corn is also coupled with increasing concentration of sugars in cell and stem tissues, which requires more energy to boil water in the cell [56]. A propane dose of 60 kg ha^{-1} caused yield losses of 6, 11, and 20 % for the V7, V5, and V2 stages, respectively. From a practical standpoint, the 6 % yield reduction of sweet corn flamed broadcast at the V7 stage may not be acceptable by organic growers. However, yield reductions were the result of the intentional flaming directly over the crop. An alternative might be to direct the flame below the crop canopy in order to spare foliage from the heat, which could result in lower yield losses (e.g., <5 %).

It is important to understand that propane flaming should not be the only method for nonchemical weed control; it should be a part of an IWM program. Other measures are still needed to control weeds that emerge later during the growing season. More research is needed to perhaps develop new flaming equipment and methods, or to examine different positioning of the burners to avoid any significant crop damage and yield reductions. Information from such research would expand flaming options as part of an IWM program for both organic and conventional crop production systems.

Biological Control

The biological control approach makes use of the weed's naturally occurring enemies to help reduce the weed's impact on agriculture and the environment. It simply aims to reunite weeds with their natural enemies and achieve sustainable weed control. These natural enemies of weeds are often referred to as biological control agents. For example, a commercial bio-herbicide Colego, a fungal herbicide, has been used to control northern jointvetch (*Aeschynomene americana* L.) in rice (*Oryza sativa* L.) in the southern USA [57]. It is critical that the biological control agents do not become pests themselves. Considerable host-specificity testing is mandatory as per many government rules and regulations prior to the release of biological control agents to ensure that they will not pose a threat to nontarget species, such as native and agricultural plants. Not all weeds are suitable for biological control. Developing a biological control project requires a substantial investment, sometimes costing millions of dollars. Currently, there are no commercial products for biological weed control in corn, though this area offers great potential for new weed control options in the future.

Chemical Weed Control

Application of herbicides is the most important method of weed control in corn. Herbicides have been adopted by a majority of corn growers in the USA and many other parts of the world because they are effective and economical. Herbicides can be applied at different time intervals, such as before the crop is planted (preplant), after the crop is planted but before emergence (preemergence), and after crop emergence (postemergence). The choice of herbicide application timing depends on many factors and varies from grower to grower and field to field. Many corn growers use more than one herbicide applications that may provide a season-long weed control.

Preplant Herbicides

For control of winter annuals and early-spring annual weeds, herbicides applied on emerged weeds are known as "burndown herbicide treatment." Foliar active herbicides, such as glyphosate, 2,4-dichlorophenoxyacetic acid (2,4-D), or dicamba, are the most common herbicides used as burndown before planting corn. Many farmers include residual herbicides with early-spring burndown treatments. While this may provide a clean seedbed at planting and crop emergence, the longevity of weed control is likely to be shortened significantly. The magnitude of this reduction will depend on the time period and weather encountered between application and planting and the herbicide rate [58]. The rates of many residual products have been reduced due to the reliance on postemergence products, primarily glyphosate in glyphosate-resistant corn. If applications are to be made a few weeks earlier than normal, the product rates should be evaluated carefully in order to maximize the contribution of the residual weed control after crop emergence.

If the residual herbicide is applied before planting corn and is incorporated in the soil with light tillage, it is known as the preplant incorporated method of herbicide application. With this application method, the herbicide is applied to the soil surface and mechanically incorporated into the top 5–8 cm of soil with tillage. Preplant incorporation is a preferred method in corn production where spring rainfall is limited and, therefore, the likelihood of adequate rainfall to incorporate herbicides is low. In addition, it also reduces the chance of herbicide loss through volatilization. For example, in Kansas and Missouri, herbicide incorporation is proposed as one of the best management practices to reduce herbicide runoff from soils with poor internal drainage [59]. Buttle observed that soil incorporation led to a significant reduction in the total metolachlor loss in runoff water relative to application as preemergence [60]. However, in recent years, preplant incorporation has declined in part due to increases in no-tillage and reduced-tillage production systems.

Preemergence Herbicides

Herbicides applied after corn planting, but before emergence and having soil residual activity, are known as preemergence herbicides. Soil-applied preemergence herbicides may either be broadcast on the field or be applied in bands over the planted crop rows. Preemergence herbicides require irrigation or rainfall within 7–10 days of application to activate herbicides and enter the weed germination zone by water infiltration [58]. If there is no rainfall or source of irrigation, mechanical incorporation by a rotary hoe can move some of the herbicide into the weed germination zone. The preemergence herbicides will have little or no foliar activity, so they will not be effective for the control of already emerged weeds at the time of application. If weeds are emerged at the time of application, preemergence herbicide can be tank-mixed with foliar active herbicides to expand weed control spectrum. Excess rainfall can reduce weed control efficacy of preemergence herbicides and increase the risk of corn injury. Several preemergence herbicides have been registered for weed control in corn (Table 8.2). Due to wet soil conditions or other factors, it is quite often that many corn growers are not in a position to apply preemergence herbicides prior to corn emergence. Several residual preemergence herbicides can be applied after corn emergence (Table 8.3). For example, herbicides (e.g., atrazine and mesotrione) have foliar activity on small, emerged weeds.

Metolachlor, alachlor, and dimethenamid are acid amide herbicides, also known as chloroacetamide herbicides. The acid amide herbicides have much more activity on grass weeds, such as crabgrass (*Digitaria sanguinalis* [L.] Scop.), barnyardgrass (*Echinochloa crus-galli* [L.] Beauv.), and broadleaf signalgrass (*Urochloa platyphylla* [Munroex C. Wright]). Tank-mixing these herbicides with

Table 8.2 List of preemergence herbicides registered for weed control in corn [64]

Herbicide	Commercial product kg per hectare		
	Sandy loam	Silt loam	Silty-clay Loam
	<1% OM	1–2% OM	>2% OM
Atrazine[a]	[b]Do not use	1.12–2.46	1.12–2.46
Isoxaflutole[b]	0.21	0.21–0.35	0.21–0.42
Isoxaflutole[b] +	0.07–0.21	0.21–0.35	0.21–0.42
Atrazine[a]	1.12	1.45	1.70
S-metolachlor + atrazine[a]	4.06	4.06–4.74	4.74
Mesotrione alone or with	0.42	0.42	0.42
S-metolachlor + atrazine	1.13	1.46	1.46
Thiencarbazone + isoxaflutole[b]	0.23	0.23–0.40	0.23–0.40
Thiencarbazone + isoxaflutole + trazine[a]	2.26	2.26	2.26
Acetochlor	2.60–3.61	3.61–4.52	3.61–4.52
Acetochlor + atrazine[a]	6.10	7.91	7.91
S-metolachlor + benoxacor	1.13	1.46	1.46
S-metolachlor + glyphosate + atrazine[a]	5.65	6.78	8.47
Flumioxazin + pyroxasulfone	0.21	0.21	0.21
Encapsulated acetochlor + atrazine[a]	5.65–6.10	6.10–7.45	6.78–7.91
Dimethenamid-P + atrazine[a]	2.26	2.82	3.95
Dimethenamid-P + atrazine[a]	2.71–3.16	3.16–3.84	3.84–4.52
Acetochlor + MON 13900 safener	1.41–1.97	1.97–2.54	1.97–2.54
Acetochlor + atrazine + MON 13900 safener	4.06	4.06–5.19	4.52–5.19
Flumetsulam + clopyralid	0.28	0.28	0.28–0.35
Acetochlor + atrazine + dichlormid	4.97–5.42	5.42–6.32	5.87–6.78
S-metolachlor + mesotrione + atrazine	6.78	6.78	6.78
S-metolachlor + mesotrione + atrazine	5.65	5.65	5.65–6.78
Dimethenamide-P	0.70–0.98	0.98–1.12	1.12–1.26
Rimsulfuron + isoxaflutole	Do not use	0.11–0.17	0.11–0.18
Pendimethalin + atrazine	Do not use	4.06	4.06
Rimsulfuron + atrazine	Do not use	0.07–0.10	0.07–0.10
Saflufenacil	0.14	0.17	0.21
Acetochlor + dichlormidsafener + flumetsulam + clopyralid	1.70	1.70–1.97	2.26
Acetochlor + dichlormidsafener	1.70–2.82	1.70–2.82	1.70–3.10
Acetochlor + dichlormidsafner alone or with	2.26	4.52–5.65	5.08–6.78
atrazine	1.23	1.45	1.68
Clopyralid + flumetsulam + acetochlor	1.70	1.97	2.26
Saflufenacil + dimethenamid-P	0.7	0.91	1.12
S-metalochlor + mesotrione + benoxacor (safener)	4.52	4.52	4.52

OM organic matter

[a] Do not apply atrazine within 20 m of where water runoff from a field will enter a stream, river, or standpipe. The total amount of atrazine (active ingredient per hectare) applied cannot exceed 2.8 kg ai/ha per calendar year. Use no more than 1.80 kg ai/ha on highly erodible land with less than 30% crop residue. Using atrazine on soils with less than 1% organic matter increases carryover injury risk to susceptible crops, especially high pH soils. Do not use on sandy soils if water table is less than 30 ft

[b] Do not use isoxaflutoleon coarse-textured soils of less than 2% organic matter if the water table is less than 7.6 m. Do not use on fields prone to runoff or flooding. Crop response is most likely to occur where soils are coarse, organic matter content is less than 1.55%, and the pH is greater than 7.4. Corn seed must be covered with 3–5 cm inches of soil. Avoid planting when soil surface is wet

Table 8.3 List of preemergence herbicides also registered for postemergence (in-crop) application in corn [64]

Herbicide	Crop stage	Maximum weed stage
Atrazine	0–30 cm	4 cm
Isoxaflutole[a]	V2	4 cm
S-metolachlor + atrazine	0–30 cm	Two-leaf
Acetochlor + atrazine + dichlormid	0–28 cm	Unemerged
Mesotrione[b]	0–76 cm	13 cm
Thiencarbazone + isoxaflutole	V2	4 cm
Acetochlor	0–28 cm	Unemerged
Acetochlor + atrazine	0–28 cm	Two-leaf
S-metolachlor + benoxacor	0–101 cm	Unemerged
S-metolachlor + glyphosate + atrazine	0–30 cm	15 cm
Encapsulated acetochlor + atrazine	0–28 cm	Unemerged
Dimethenamid-P + atrazine	0–30 cm	4 cm
Acetochlor + atrazine + MON 13900 safener	0–28 cm	Two-leaf
Flumetsulam + clopyralid	0–5 cm	20 cm
Acetochlor + atrazine + dichlormid	0–28 cm	Unemerged
S-metolachlor + mesotrione + atrazine	0–30 cm	7 cm
Dimethenamide-p	0–30 cm	Unemerged
Pendimethalin	0–76 cm	3 cm
Flumetsulam	0–51 cm	15 cm
Rimsulfuron	0–30 cm	7 cm
Atrazine + metolachlor	0–13 cm	Two-leaf
Acetochlor + dichlormidsafener + flumetsulam + clopyralid	0–28 cm	5-cm broad leaves
Acetochlor + dichlormidsafener	0–28 cm	Unemerged
Atrazine + metolachlor	0–13 cm	Two-leaf
Actochlor + atrazine + safener	0–28 cm	Unemerged

[a] If isoxaflutole is applied after the corn has emerged, do not add oil concentrate
[b] Severe injury may occur if mesotrione is applied postemergence to corn that has been treated with Counter. Do not tank-mix with any organophosphate or carbamate insecticide. Do not cultivate within 7 days of application

atrazine-applied preemergence can provide effective broad-spectrum weed control for about 3 weeks after application. Soil texture, pH, and organic matter content are the soil properties most commonly used to determine the application rates of preemergence herbicides. For example, isoxaflutole, a preemergence herbicide of corn, showed a considerable crop injury [61, 62]. It was concluded that isoxaflutole rates should be carefully selected for soils with low organic matter and high pH [63]. In the past few years, several preemergence herbicides have been tank-mixed with postemergence herbicides and are now available as a prepackaged mixture that expands weed control spectrum and provides more flexibility with application timing (Tables 8.2 and 8.3).

Postemergence Herbicides

Herbicides applied after corn and weed emergence are known as postemergence herbicides. They usually have foliar activity on emerged weeds with a good crop safety if applied as directed on the label. Postemergence herbicides can be broadcast-applied on crop and weeds or with the equipment that directs the herbicide to weeds and minimizes exposure of the crop [64]. Foliar-applied postemergence herbicides do have a requirement for rainfall after application. In fact, a certain time is required after application of postemergence herbicides that should be free from rainfall or overhead irrigation to avoid washing the chemicals of the plant and leaf surface. For example, time until herbicides are rainfast for 2,4-D is 1 h, glyphosate 1–4 h depending on glyphosate formulation, and glufosinate 4 h. Several postemergence herbicides have been registered for weed control in corn (Table 8.4).

Wide-scale adoption of glyphosate-resistant corn has resulted in heavy reliance on glyphosate for weed control for many years in Midwestern United States. Multiple glyphosate applications are relied upon for weed management in glyphosate-resistant corn, which comprise approximately 60 % of the corn hectares in the USA. In addition, more than 90 % of the soybean hectares are planted with glyphosate-resistant cultivars, placing extreme selection pressure for glyphosate resistance in weeds. Although corn and soybean are commonly rotated in North Central and Midwestern USA, corn for seed production is continually grown on the same land without rotation with other crops. The hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides, such as mesotrione, tembotrione, topramezone, and isoxaflutole, are important herbicides for control of broadleaf weeds in grain and seed corn.

Atrazine has been in use since 1958 and is applied on several million hectares in the USA and several other counties. Atrazine is the base for the weed control program in corn in the USA. It is widely used because of its low cost, control of a broad spectrum of broadleaf weeds, flexible application timing, such as preemergence or postemergence, and compatibility to mix with several other herbicides. However, a long-term and continuous use of atrazine resulted in accumulation of atrazine and its breakdown products in the environment, groundwater, and aquatic systems [65, 66]. In the USA, a recent national survey of leopard frogs (*Rana pipiens*), a species sensitive to atrazine, has shown that defects linked to atrazine exposure tended to be greater in areas of high atrazine use [67]. Therefore, the use of atrazine for crop production has been banned in several European countries, including France, Germany, Italy, and Sweden. A 3-year study conducted in Canada reported that the addition of atrazine to preemergence herbicides increased weed control (25 %), improved herbicide performance consistency, increased corn yields (8 %), increased adjusted gross return, and reduced risk over sites and years [68]. More research is required to explore the potential of reducing atrazine-use rates while maintaining effective weed control in corn and environmental quality.

Although atrazine effectively controls many broadleaf and some grass weeds, it has been inconsistent for the control of velvetleaf, common cocklebur, and *Ipomoea* spp. Because most corn growers have a number of broadleaf and grass

Table 8.4 List of postemergence herbicides registered for weed control in corn [64]

Herbicide	Rate kg per hectare	Application time
2,4-D ester or 2,4-D amine	0.56–1.12	Spike to 91 cm corn; broadleaf weeds 2–6 leaves
Nicosulfuron	0.05	Corn 10–91 cm (V10); if greater than 50 cm, use drop nozzle
Nicosulfuron + atrazine[a]	0.06 1.23	With atrazine, corn less than 30 cm
Carfentrazone-ethyl	0.03	Corn less than V14, but if greater than V8, use drop nozzles; broadleaves 2–10 cm; velvetleaf up to 90 cm
Atrazine[a]	1.60–2.5	Corn less than 30 cm; broadleaves 5–15 cm; grass weeds 2 cm or less
Atrazine[a] + dicamba[b]	0.62–1.12 + 0.63–1.12	Corn less than V5
Rimsulfuron (50 %) + thifensulfuron (25 %)	0.02	Corn spike to V2; grasses 2–5 cm; broadleaves 2–8 cm
Primisulfuron 75 %	0.03–0.05	Corn 10–50 cm; shattercane 10–30 cm; broadleaves 2–10 cm; grasses 2–8 cm
Bromoxynil + atrazine[a]	1.13–1.70 + 0.61–1.23	Corn three-leaf to 30 cm Broadleaves 5–15.24 cm
Bromoxynil + dicamba[b]	1.13–1.70 + 0.60	
Fluthiacet-methyl	0.04–0.06	Corn emergence to 120 cm
Mesotrione	0.21	Corn to 75 cm or V8; broadleaves less than 12 cm
Mesotrione + atrazine[a]	0.17 + 0.56	Corn less than 30 cm
Thiencarbazone-methyl tembotrione	0.21	V1–V6
Clopyralid + MCPA	2.26	Spike to V4
Dicamba[b]	0.56–1.12	Spike to 90 cm; if greater than 20 cm, use drops
Dicamba[b] + 2,4-D ester or amine	0.56 + 0.3 or0.30	Broadleaves 2–6 leaves
Diflufenzopyr + dicamba	0.42 + 0.30	Corn 10–25 cm; corn 25–60 cm; if 60–90 cm, use drops
S-metolachlor + glyphosate[c] + atrazine (glyphosate-resistant corn only)	6.21–8.50	Corn 0–30 cm
Glyphosate[c](glyphosate-resistant corn only)	Up to 3.40	Corn to 122 cm (V12); if over 60 cm, use drops
S-metolachlor + glyphosate[c] + mesotrione (glyphosate-resistant corn only)	4.10–4.52	Corn to 76 cm (V8); before weeds exceed 10 cm
Flumetsulam + clopyralid	0.14–0.35	Spike to 50 cm, if greater than 50 cm use drops; broadleaf weeds less than 20 cm
Topramezone	0.05–0.07	Broadleaf weeds 5–15 cm; for corn 60–71 cm, apply with drop nozzles
Topramezone + atrazine[a]	0.05 + 0.33–1.80	Corn less than 30 cm

Table 8.4 (continued)

Herbicide	Rate kg per hectare	Application time
Tembotrione	0.21	Corn emergence V8; broadleaf weeds less than 15 cm; grass weeds less than 8 cm
Tembotrione + atrazine[a]	+ 0.56	Corn less than 30 cm; weeds 2–8 cm
Tembotrione + bromoxynil	0.14 + 0.42	Corn less than 30 cm; weeds 2–15 cm
Glufosinate (Liberty Link hybrid required)	1.54–2.03	Corn at 60 cm (V7); for corn 60–90 cm, use drop nozzles to avoid spraying in whorl
Glufosinate (Liberty Link hybrid required) + tembotrione	1.54–1.70 0.10–0.21	Up to 60 cm (broadcast) or 75 cm (drops); weeds 2–10 cm
Imazethapyr + imazapyr alone (Clearfield hybrid required) or with dicamba[b]	0.08 0.56–1.12	Corn up to 50 cm (V6); weeds up to 10 cm; weeds to 10 cm
Foramsulfuron	0.09–0.12	Corn 0–90 cm, if greater than 40 cm, use drops; weeds less than 10 cm
Halosulfuron	0.05–0.09	Corn spike lay-by greater than 50 cm use drops; broadleaf weed 5–15 cm
Rimsulfuron + mesotrione	0.28	Corn up to 50 cm or V7
Rimsulfuron + dicamba[b]	0.28	V2–V7 corn; 2–8 cm weeds
Rimsulfuron + thifensulfuron	0.08	Corn up to 50 cm or V7
Flumiclorac	0.28–0.42	Corn V2–V10; broadleaf weeds less than 10 cm
Rimsulfuron	0.07	Corn up to 30 cm or V6, whichever is most restrictive
Prosulfuron + primsulfuron	0.07	Corn 10–60 cm; if greater than 50 cm (V6), use drops; weeds 5–20 cm
Fluroxypry + bromoxynil	0.45	VE–V5 corn; sweet corn up to V4; weeds less than 20 cm
Diflufenzo-pyr + dicamba[b] + isoxadifen	0.17	Corn 10–90 cm
Nicosulfuron + rimsulfuron	0.05–0.10	Corn to 50 cm or V6; weeds 5–10 cm
Nicosulfuron + acifluorfen	0.05–0.10	Corn to 40 cm or V5
Fluroxypyr + clopyralid	1.50	Corn spike to V5; weeds less than 20 cm
Halosulfuron + dicamba[b]	0.28–0.56	Spike to 90 cm; weeds 2–15 cm

OM organic matter

[a] Do not apply atrazine within 66 ft of where water runoff from a field will enter a stream, river, or standpipe. The total amount of atrazine applied (active ingredient per hectare) cannot exceed 2.8 kg ai/ha per calendar year. Use no more than 1.8 kg ai/ha on highly erodible land with less than 30 % crop residue. Using atrazine on soils with less than 1 % organic matter increases carryover injury risk to susceptible crops, especially high pH soils. Do not use on sandy soils if water table is shallower than 30 ft

[b] Dicamba rates are based on a 4.5–3.4 kg ae/ha formulation

[c] Glyphosate rates are based on a 4.5–3.4 kg ae/ha formulation

weed species in their fields, tank-mixing atrazine with other herbicides—such as mesotrione, isoxaflutole, or acetochlor—might be desirable to broaden the weed control spectrum. Mixtures of two or more herbicides may provide more consistent control of certain weeds, reduce the risk of evolving weed resistance, and may reduce the amount of total active ingredient applied [69, 70]. Synergistic interactions have been observed between mesotrione- and atrazine-applied postemergence for the control of velvetleaf, sunflower (*Helianthus annuus* L.), and Palmer amaranth [71]. Furthermore, tank-mixing atrazine with mesotrione-applied preemergence in corn increased the control of common ragweed (*Ambrosia artemisiifolia*), common lambsquarters (*Chenopodium album* L.), and *Ipomoea* spp. [72]. Several new herbicides have been registered for weed control in corn in the past few years that are tank mixtures of existing herbicides (Table 8.3) [64].

Herbicide Injury

Corn plants are occasionally injured by herbicides. To minimize crop injury, herbicides must be applied uniformly at the stage of crop growth specified on the label. Unfavorable conditions, such as cool, wet weather, delayed crop emergence, deep or shallow planting, seedling diseases, soil in poor physical condition, and poor quality seeds, may contribute to crop stress and herbicide injury. Corn hybrids and cultivars may vary in their tolerance to herbicides and environmental stress. Crop planting options for next season also must be considered when selecting the herbicide program. Corn herbicides may have restrictive cropping intervals for some agronomic and many vegetable crops.

Multiple Herbicide-Resistant Corn

Since 1998, genetically modified herbicide-resistant corn, primarily glyphosate-resistant, has helped to revolutionize weed management and has become an important tool in corn production practices in the Americas [73]. Glyphosate has performed long and well, but due to its widespread and repeated use, 13 weed species in the USA have evolved resistance to glyphosate and 23 species worldwide by 2012 [74]. Unfortunately, most companies are not developing any new selective herbicides with new modes of action that can be effective for the control of glyphosate-resistant weeds [75]. However, they are developing new multiple herbicide-resistant corn traits through genetic engineering to combine with glyphosate resistance and expand the utility of existing herbicides [76]. For example, glyphosate plus glufosinate-resistant corn is already available in the market.

Despite the fact that auxin group herbicides, such as 2,4-D and dicamba, have been used for many years, only a few weed species have evolved resistance to this group of herbicides. Efforts are under way to commercialize 2,4-D plus glyphosate-resistant corn and soybeans, known as Enlist™ System as well as dicamba + glyphosate-resistant corn and soybeans, known as Roundup Ready™ 2 Xtend System. There are several controversies prevailing about multiple herbicide-resistant corn and soybeans that are currently pending regulatory approval. Many groups and individuals are concerned, and they argue that multiple herbicide-resistant crop varieties will make growers more dependent on the intellectual property held by large corporations, will injure nontarget crops due to drift and volatility of 2,4-D and dicamba, and will accelerate the evolution of multiple herbicide-resistant weeds [77, 78]. Others argue that multiple herbicide-resistant crop cultivars will help growers controlling herbicide-resistant weeds. The message is clear that no weed management technology used alone is sustainable since weeds will adapt to any single tactic used repeatedly for many years. Therefore, an IWM approach is required for sustainable corn production to meet the growing demand.

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