Integrated Weed Management Guide for Mid-Atlantic Grain Crops

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Chapter 1: An Introduction to Integrated Weed Management

Annie Klodd and Mark VanGessel

Summary

Weed control includes tactics such as herbicides, cultivation, or flaming. Weed control is usually immediate and often does not require long-term planning. On the other hand, weed management includes a wider range of tactics, many that do not cause immediate plant death, but rather they place the weed at a competitive disadvantage. Integrated weed management uses multiple strategies that reduces the emphasis of any one tactic and provides for more consistent results over a wider range of environmental conditions.

Introduction

Weed control and weed management are often used interchangeably, but they are two different approaches to preventing weeds from interfering with crop production. Weed control involves killing weeds with tools or tactics that have an immediate impact. Weed management involves a longer timeframe (the entire growing season or longer) and individual tactics may not kill weeds on their own. Rather the crop is managed in a manner that allows it to capture sunlight, moisture, or nutrients and improve the crop’s competitiveness with weeds. Weed control is often an active process with the farmer taking direct action, while weed management is often a more passive process.

Integrated weed management (IWM) combines various methods to reduce or eliminate the effect of weeds on crop production over time, using a combination of practices that are most effective for solving specific weed issues. These weed management techniques form a “toolbox” in which each “tool” can be integrated into a weed management plan catered to the particular farm and problem. The toolbox includes prevention, biological, chemical, cultural, and mechanical strategies. IWM also considers which weed species are present and tailors these strategies for these species.

There are many reasons for implementing IWM, including farmers that do not want to use herbicides, crops that have limited herbicide options, managing weeds that have poor or no herbicide options (including herbicide-resistant biotypes), and reducing the risk of selecting for herbicide-resistant weeds. Farmers need to determine their objectives when implementing IWM and use tactics that will help them to meet those objectives. Even if a field does not currently have problem weeds, IWM will help
to prevent overreliance on any particular practice or tactic that could lead to the increase of specific weeds.

In conventional crops, integrated weed management is not a replacement for herbicides. For many decades, herbicides have been the primary means of weed management in conventional crops due to their simplicity, effectiveness, and affordability. However, over relying on herbicides have led to selecting for weed species that are not effectively controlled with the herbicide program or selecting for herbicide-resistant biotypes. Relying merely on herbicide rotation and mixtures for weed control is not an IWM approach. IWM is about using all methods available to best solve the problem – in many cases with conventional crops, herbicides are part of this solution.

IWM tactics span a wide range of types and complexity (Figure 1.1). When these tactics overlap and complement one another, is when IWM will have the biggest impact. Some examples of IWM tactics include equipment cleaning, timely scouting, altering herbicide tank-mixtures, rotating herbicides, using cover crops, changing tillage practices, and hand-pulling weeds.

Some IWM practices are capable of controlling actively growing weeds, such as herbicides, cultivation, tillage, or biological agents. Others are passive in nature, as having an indirect effect on the weeds such as cover crops, crop rotations, or many cultural practices.

Many agronomic practices will have a direct or indirect influence on weeds. These practices may be done solely for other purposes, but in turn they impact weeds. Agronomic practices that favor a quick crop canopy to shade the ground or weed seedlings are very important, including narrow row spacing, crop varieties with early-season vigor, and altering planting dates. Understanding how these practices fit together can lead to more informed decisions and help to fine-tune systems.

IWM needs to have a longer view for weed management. IWM is not only concerned with weed control for the short term, but the management practices also
impact crop management and weed control will have on weed communities in subsequent years.

IWM tends to be more site specific than weed control practices that rely heavily on one tactic. Differences from field to field, as well as within fields, requires a better understanding of how the tactics of IWM interact.

There is a continuum of intensity for IWM. Some farmers may focus on only a few IWM tactics and have a low level of IWM utilization. Understanding how these tactics or practices can complement one another, will maximize their effectiveness and increase the level of IWM utilization. High level of IWM utilization will lessen the risk of allowing weeds to produce seeds without relying on a specific tactic. Relying on only one tactic will often result in one (or a few weed species) to produce seed and increase in density. This phenomena is often referred to as selection pressure and species shift.

Key Points

- Weed control involves tactics that cause immediate plant death and does not require long-term planning.
- Integrated weed management requires planning from weeks ahead of time to years in advance.
- Integrated weed management often focuses on reducing the growth and vigor of weeds; and allowing the crop to outcompete the weeds.
Chapter 2: Identification and Characteristics of Weeds

*Michael Flessner*

**Summary**

Weed identification is essential for development of a successful management plan. Identification of all weeds present lends information on how to best manage individual weeds and the weed population as a whole. Similarly, knowledge of weed characteristics allow the manager to exploit weaknesses or avoid strengths of a weed, when making management decisions. It is important to have resources available to aid in weed identification.

**Introduction**

The first step to planning a successful weed management program is weed identification. Weeds vary widely in their responses to individual management techniques. Without proper identification of all weeds present in the field, control measures are likely to fail (Ross and Lembi 1985). Characteristics of each weed, correctly identified can be used to better manage both individual weeds and the overall weed population. For example, a weed’s life cycle (annual, biennial, or perennial) can drastically influence the effectiveness of an herbicide application. A weed’s germination period can be used to alter tillage operations in a stale seed bed approach or alter planting date to avoid weed competition.

**Weed Identification**

Weed identification in practice can be very difficult. Weeds can vary their appearance greatly between different growth stages and environments. A basic knowledge of plant characteristics will vastly improve the effectiveness of the resources listed below. Proper scouting (see Chapter 4: Weed Scouting and Mapping) is the best method for timely identification.

**Weed Identification Resources**

In addition to local extension agents, the local co-op, friends and neighbors, there are a number of excellent resources available; and many of them are available free on line. A list of these resources are available in the appendix at the end of this chapter.
Characteristics of Weeds

Most plants are not weeds. A weed is simply an undesirable plant. One person’s weed may be another’s flower. Therefore, designating a plant as a weed is somewhat arbitrary. Worldwide, only about 250 species or 0.1% of plants are economically important weeds. Weeds can vary greatly among different growth stages and environments. Proper scouting is the best method for timely identification (see Chapter 4, Weed Scouting and Mapping).

Certain characteristics allow a plant to behave as a weed. Weeds possess one or more of the following:

### Abundant seed production

Most weeds, especially annuals, are prolific seed producers (Table 2.1)

### Rapid population establishment

Weeds can germinate and establish quickly, especially under favorable weather conditions. Left unchecked, weeds will outcompete crops. Even under unfavorable environmental conditions weeds can produce viable seed in as little as six weeks.

### Seed dormancy

Various mechanisms of seed dormancy ensures a weed does not germinate under unfavorable or lethal environmental conditions. Seed dormancy also ensures that not all of a weed population germinates at the same time, which results in weeds emerging throughout times of favorable conditions.

### Long-term survival of buried seed

Most seeds do not live for more than three to four years due to germination, predation, decomposition, and other factors. However, there are some weed seeds than can remain viable for many years if left undisturbed (Figure 2.1 and Table 2.2)

**Table 2.1. Seed production from various weed species. Adapted from Ross and Lembis page 6 *Bhowmik and Bekech 1993**

<table>
<thead>
<tr>
<th>Weed</th>
<th>Approximate number of seeds per plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barnyardgrass</td>
<td>7,000</td>
</tr>
<tr>
<td>Giant foxtail</td>
<td>10,000</td>
</tr>
<tr>
<td>Common ragweed</td>
<td>15,000</td>
</tr>
<tr>
<td>Velvetleaf</td>
<td>17,000</td>
</tr>
<tr>
<td>Curly dock</td>
<td>40,000</td>
</tr>
<tr>
<td>Common lambsquarters</td>
<td>72,000</td>
</tr>
<tr>
<td>Redroot pigweed</td>
<td>117,000</td>
</tr>
<tr>
<td>Horseweed</td>
<td>200,000*</td>
</tr>
<tr>
<td>Palmer amaranth</td>
<td>600,000</td>
</tr>
</tbody>
</table>
Adaptation for spread

Weed seeds spread by natural forces such as wind and water or clinging to animals (Photos 2.1, 2.2, 2.3). Weed seed can also be spread by passing through the gut of animals. For example, Palmer amaranth is reported to have less than 60% viability after passing through deer and have been found in the guts of 11 different bird species including migratory birds (DeVlaming and Vernon 1968; Farmer et al. 2017; Proctor 1968).

Importantly, weeds are spread by farm equipment (Ross and Lembi 1985). Some weeds have evolved to produce and retain seed on the plant at the same time as crops, resulting in seed spread with harvest equipment. Bush hogging and other pieces of equipment also commonly spread weed seeds. Keep equipment free of weed seeds. For more information (see Chapter 6: Prevention of Weeds).
Vegetative reproductive structures

Most perennial weeds possess special vegetative structures that allow them to reproduce asexually and survive. These perennial structures contain food reserves and have numerous buds in which new plants can arise. Examples of these vegetative structures are listed in Photo 2.4 A-E.

In addition to these vegetative reproductive structures, many perennials reproduce by seed. Some depend heavily on reproduction by seed (e.g. dandelion), while for others it is less important (e.g. yellow nutsedge).
Photo 2.4. Perennial weed structures including A. stolons, B. rhizomes, C. tubers, D. budding roots, and E. bulbs.

A. Stolons
Above ground horizontal stems that root at the nodes. Bermudagrass stolon. (Photo credit: Virginia Tech, Weed Science)

B. Rhizomes
Below ground thickened stems that grow horizontally near the soil surface. Quackgrass with rhizome. (Photo credit: Virginia Tech, Weed Science)

C. Tubers
Yellow nutsedge with tuber. (Photo credit: R. Prostak, Univ of Mass)

D. Budding roots
Hemp dogbane budding roots. (Photo credit: Penn State, Weed Science)
Classification of Weeds

Life cycle

While weeds can be classified in many ways, a weed’s life cycle is perhaps the most important factor in planning an effective weed management program, as a weed’s susceptibility to a management tactic varies by life cycle and time of year.

Annual. Annual weeds germinate, produces seed, and die in less than a year (Photo 2.5; Table 2.4). Annuals are competitive in disturbed sites common in annual cropping systems, such as tilled fields or those burned down with herbicide. Annuals are also competitive in perennial cropping systems during the crop’s dormant period, such as during the winter in alfalfa.

Winter annual weeds typically germinate in late summer or fall and produce seed the following spring. Some winter annual weeds, such as horseweed (also known as marestail), can germinate in early spring.

Summer annuals germinate in late spring or summer. Some summer annuals, such as foxtails, are capable of multiple generations in a single growing season.
Biennial. A biennial weed completes its life cycle in two years (Table 2.4). Germination and establishment occur in the first year, typically resulting in a rosette growth stage (Photos 2.6 and 2.7). In the second year, the weed flowers, produces seed, and dies. Biennials start each life cycle from seed and are most competitive in areas of infrequent management such as roadsides, pastures, or hayfields.
**Perennial.** Perennials live for longer than two years and may live indefinitely. Perennials have various structures, many times underground, that the plant can regenerate from year after year (see perennial structures below). Their persistence and spread is not as dependent upon seed as annuals or biennials. Perennial weeds take longer to establish by seed compared to annuals, making them more common in undisturbed areas, such as within other perennial crops. Once established in no-till systems common in the Mid-Atlantic, they can be extremely difficult to control; successful control requires killing the underground parts as well as the above ground vegetation.

Perennial weeds can be divided into two groups: simple and creeping. Simple perennials form a deep taproot and spread primarily by seed dispersal. Creeping perennials may be either herbaceous or woody and can spread by both seed and vegetative structures, such as rhizomes or stolons (Photo 2.4 A-E).

Perennial species emerging from seeds can quickly develop their perennial characteristics of vegetative reproductive structures. Some species can begin to develop their structures as soon as four weeks after emergence (Bhowmik 1994; Donald 1994).
Table 2.4. Examples of common weeds classified by life cycle.

<table>
<thead>
<tr>
<th>Annuals</th>
<th>Biennials</th>
<th>Simple</th>
<th>Creeping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>Summer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grasses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annuals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bluegrass</td>
<td>crabgrass</td>
<td>burdock</td>
<td>chicory</td>
</tr>
<tr>
<td>annual</td>
<td></td>
<td>poison</td>
<td>common</td>
</tr>
<tr>
<td>ryegrass</td>
<td>foxtails</td>
<td>hemlock</td>
<td>pokeweed</td>
</tr>
<tr>
<td>cheat</td>
<td>barnyardgrass</td>
<td>teasel</td>
<td>curly dock</td>
</tr>
<tr>
<td>downy brome</td>
<td>goosegrass</td>
<td>bull thistle</td>
<td>dandelion</td>
</tr>
<tr>
<td></td>
<td>fall panicum</td>
<td>wild carrot</td>
<td>plantain</td>
</tr>
<tr>
<td>Broadleaves</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>common chickweed</td>
<td>cocklebur</td>
<td>common lambsquarters</td>
<td></td>
</tr>
<tr>
<td>henbit</td>
<td></td>
<td>common horseweed</td>
<td></td>
</tr>
<tr>
<td>or marestail</td>
<td>ragweed</td>
<td>mustards pigweeds</td>
<td></td>
</tr>
</tbody>
</table>

Most Effective Weed Control Timings and Methods Based on Life Cycle

The effectiveness of a weed control practice depends on the life cycle of the weed and what growth stage is targeted. Annual weeds as well as biennial and perennials reproducing from seed are most effectively controlled when the weed is young and actively growing. At this time, it is generally susceptible to many control techniques, including tillage, herbicides, flaming, and others. For annuals, once the weed flowers, it is much more difficult to control. Once a weed flowers, it is difficult to stop viable seed production.

Biennial weeds are most susceptible when young and actively growing or in the rosette stage (Photos 2.6 and 2.7).

Established perennial weeds are generally most susceptible to herbicides once energy reserves in their underground structures have been depleted and used to develop aboveground stem growth. Herbicide should be applied to most established
perennials during the early-budding (just prior to flowering) to flowering stage. Alternatively, autumn applications take advantage of the plant’s sugar movement to underground storage structures, which can take herbicide to these otherwise difficult to reach structures. Mowing established perennials requires multiple and consistent cuttings to effectively starve the plant (see Chapter 13: Pre- and Post-Plant Mechanical Weed Control).

Key Points

- Weed identification is essential for development of a successful management plan.
- Weeds have many characteristics that make them successful in our cropping systems.
- The life cycle and growth stage of a weed largely determines optimum timing of control measures.
- Weeds emerging from seed are most susceptible to control tactics early in their life stage and actively growing.
- Established perennial weeds are more difficult to control and generally require multiple, sequential, and well-timed control tactics, so identification is important.
- Successful control of established perennial weeds requires depleting the food reserves in the underground vegetative structures.

References


Appendix 2.1. Weed identification resources.

<table>
<thead>
<tr>
<th>Item</th>
<th>Source</th>
<th>Link</th>
</tr>
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<td><a href="https://weedid.cals.vt.edu/">https://weedid.cals.vt.edu/</a></td>
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<td>Ohio State University</td>
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</tr>
<tr>
<td>Apps</td>
<td>Virginia Tech</td>
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</tr>
<tr>
<td></td>
<td>University of Missouri</td>
<td><a href="http://weedid.missouri.edu/">http://weedid.missouri.edu/</a></td>
</tr>
<tr>
<td>Clinic</td>
<td>Virginia Tech</td>
<td>Residents of Virginia can submit a plant sample for identification to the Virginia Tech Weed Identification Clinic free of charge via their county Agent (<a href="https://www.ext.vt.edu/offices/index.html">https://www.ext.vt.edu/offices/index.html</a>).</td>
</tr>
<tr>
<td>Fee-based Services</td>
<td>University of Tennessee</td>
<td><a href="http://www.weeddiagnostics.org/Pages/Weed-Identification.aspx">http://www.weeddiagnostics.org/Pages/Weed-Identification.aspx</a></td>
</tr>
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</table>
Introduction

Weeds emerge from the soil and spend their entire life cycle in the same field. The propagules (seeds or vegetative reproductive structures) can be spread from field to field, but the weed’s life cycle starts in the soil. Weed seed germination is the sprouting of the seed followed by the seedling emergence from the soil. Emergence occurs when the seedling emerges from the soil with the hypocotyl (stem below the first leaves) and cotyledons (first leaves to develop, often different shape that later developing leaves). The seedlings grow and develop by adding new leaves, stems, and expanding their root systems. A mature plant will produce flowers followed by forming seeds and eventually die.

Environmental cues and ecological factors affect weed emergence, which does not occur uniformly over a field or are the same for all weed species. Weed seed germination and emergence depends on many complex, interrelated processes. This includes depth of the seeds in the soil, seed dormancy, soil temperature, moisture level, exposure to light, tillage intensity and timing, and crop residue or vegetation cover.

Soil Seedbank

The number of weed seeds in the soil fluctuates over time. Weed seeds are deposited into the soil from a variety of sources. As the seeds germinate and emerge they are withdrawn from the soil. Seeds also may be lost through ecological processes.
(Figure 3.1). This process of deposition and withdrawal (or loss) from the soil is referred to as the “weed seedbank” or “soil seedbank”.

Seeds are deposited from a wide range of sources. The primary source of seeds is from weeds within the field that are not controlled. “Seed rain” describes the process of seeds falling from weeds and entering the seedbank. New weed species are introduced through many different mechanisms such as wind, runoff water, wildlife, or as a contaminant (see Chapter 6: Prevention of Weeds). The number of seeds moving into a field can vary from a few seeds that may require a few years to increase in density before a farmer realizes there is a new species, to a large number of seeds moving in to the field such as wind-blown horseweed (or marestail) seeds from an adjacent field.

Age of weed seeds in the seedbanks will vary greatly. It is estimated that less than 10% of the viable seeds in the seedbank will germinate in a given year; however, many of the seeds that do germinate were deposited the previous year. Some seeds were deposited many years previously and have remained dormant in the soil. Reducing the number of seeds that are deposited into the soil is one mechanism for reducing the size of the weed seedbank, and in turn reducing the number of weeds that emerge.

Dramatically, reducing weed seed rain for one year can decrease weed densities the following year. Research with common lambsquarters and smooth pigweed seed production eliminated in a year has shown significant reduction in number of weed seedlings that emerge the following year (Teasdale et al. 2004). Sustained efforts to achieve excellent weed control over a six-year period has resulted in reducing redroot pigweed and common lambsquarters seeds in the soil by over 95% (Schweizer and Zimdahl 1983, 1984). Excellent weed control with chemical, mechanical, and cultural tactics will result in few to no weed seeds deposited into the soil. However, in situations where weed control is poor and weeds are present late in the season, killing weed seeds at harvest time is being explored as a method of reducing the number of seeds that enter the seedbank (see Chapter 14: Harvest Weed Seed Control).

**Dormancy**

Seeds are able to survive for more than one year in the weed seedbank through dormancy. Dormancy is a complex mechanism that prevents a weed seed from germinating under conditions normally favorable for seedling growth. Chemical, physical, and environmental cues will influence dormancy. Dormancy is an evolutionary trait that increases the likelihood of a species to continue its existence in a field. Weeds can remain dormant in the soil seedbank for 2 to over 25 years, depending on the species.
**Seed loss from seedbank**

Seeds are withdrawn (or loss) from the soil seedbank by a number of processes (Figure 3.1). Weed seeds are lost from the weed seedbank due to seed germination and seedling establishment, fatal seed germination (seed germinate but unable to emerge from the soil), seed decay, ingestion by vertebrates and invertebrates, or physical removal from the soil as a result of erosion or water runoff. The number of weed seeds in the soil declines more rapidly when the fields are tilled than in fields with no soil disturbance. This is presumably due to enhanced germination as a result of tillage (Roberts and Dawkins, 1967; Roberts and Feast, 1973). The tillage operation allows for greater exchange of gases, seed coat abrasion or scarification, exposure to light, improved seed to soil contact, and soil warming, all factors that can stimulate seed germination.

**Weed Seedling Emergence**

While weed species are classified by season (summer annual or winter annual) there are variations in emergence timing (See Chapter 2: Identification and Characteristics of Weeds). Soil temperature appears to play a major role in determining weed emergence timing. The soil temperature around the seed can be influenced by a number of factors including solar radiation (influence by plant canopy), soil texture, soil cover, soil density, soil moisture, and soil depth. There is a temperature threshold at which seeds start biological and chemical activity and a higher temperature that
inhibition germination and induces seed dormancy. These threshold temperatures vary by species. Temperature fluctuations (changes from daytime to nighttime) can play a role in breaking dormancy and leading to germination and emergence. The environmental conditions during seed development also influences germination, as they can impact weed seed coat hardness which in turn can influence ability of seeds to absorbed moisture and resistant seed coat abrasions.

Even when germination requirements are satisfied, seedlings only emerge if the seed is at the right depth in the soil. Generally, species with small seeds will only emerge from a soil depth of less than one inch. For instance, horseweed seeds are very small and need to be right at the soil surface to emerge. Large seeded species such as morningglory or Texas panicum can emerge from depths greater than two inches. While a deep burial of weed seeds can prevent seeds from emerging, it can also lengthen the time seeds remain viable because they are not exposed to predation or fluctuation in soil temperature and moisture. Conversely, seeds close to the soil surface endure frequent disturbance will increase germination.

Tillage systems have a tremendous impact on the depth that weed seeds are buried. In no-till systems, seeds remain at or near the soil surface. Weed seeds are concentrated in the top two inches with chisel plowing while moldboard plowing will bury weed seed deeper than four inches; although moldboard plowing over time results in fairly uniform seed distribution throughout the plow layer. Thus, tillage type affects germination and emergence. For example, common lambsquarters density increased rapidly in no-till systems compared to conventional tillage (Teasdale et al. 1991). For more information on the effect of tillage on weed seed burial, see Chapter 13: Pre- and Post-Plant Mechanical Weed Control.

For example of how to use weed emergence patterns in IWM consider a field with common ragweed and giant foxtail (Figure 3.2). Delaying planting until late May after common ragweed emergence has peaked will result in a lower plant density. On the other hand, giant foxtail emerges throughout the summer and delayed planting will not be as effective as a strategy.

Weeds that emerge within a short time period are called a cohort or flush of weeds. In Figure 3.2 there are many plants emerging in early May, with an additional
cohort for large crabgrass, giant foxtail, redroot pigweed and common lambsquarters in July.

As a group, winter annuals emerge over a longer time span than summer annuals, because they emerge in the fall and/or early spring. For example, the winter annuals henbit, field pansy (or Johnny jumpup), and downy brome emerge in the fall, while other winter annuals such as shepherd’s-purse, horseweed, purslane speedwell and field pennycress emerge during both the fall and spring (Werle et al. 2014).

Predicting the number of weeds that will emerge over a season is very difficult. Knowing the number of seeds in the soil at any one time is very challenging, and predicting the percent of seeds to germinate and successfully establish is beyond our predictability at this time. As a result research has focused on predicting weed emergence timing. Knowing when weeds emerge improves overall weed management. For instance, stale or false seedbed approaches are more effective for weed species that germinate over a period of three to four weeks, compared to species that emerge throughout the growing season (Figure 3.3) (see Chapter 13: Pre- and Post-Plant Mechanical Weed Control). In addition, understanding the emergence for weeds in a field will improve use of residual herbicides and improve timing for weed scouting.

One method of predicting weed emergence is calculating cumulative emergence, which predicts what percentage of emergence will have occurred at a specific time. As a result, most cumulative emergence curves have a general sigmoidal shape with emergence starting slowly, then a steep increase in emergence and then a leveling of emergence (Figure 3.3). In this example, 50% of the species with a short emergence period has emerged within four weeks and 100% of the plants have emerged by seven weeks. The species with a long emergence period does not reached 50% emergence until nine weeks. Common ragweed is an example of a species with a relatively short emergence span, while Palmer amaranth and horseweed are species that germinate over a long time span.

Stale seedbeds, residual herbicides at planting, or weed control tactics used within a month after planting will likely control the majority of the plants with a short emergence period. Species with a long emergence period (or multiple cohorts), typically
require a higher level of IWM utilization to achieve zero weed seed production. For instance tactics that provide maximum crop shading, longer residual herbicides, or cover crop residues that degrade slowly over time.

**Weed Communities**

Fields have many weed species present, while only a few species may dominated. Fields sampled in Ohio had over thirty weed species identified (Cardina et al. 2002). As the diversity of species increases the need for a higher level of IWM utilization also increases.

Weeds infesting a field include summer and winter annuals. Biennials and/or perennials may also be in the field. Figure 3.4 is an organizational framework to capture the diversity of plants within a field. All of the plants of one species are called a population. All of the populations of different species are called the community, and how the community interacts with the environment and agricultural production practices is call the ecosystem. Biotypes are plants within a species that are genetically distinct, for instance herbicide-resistant plants are biotypes. Weed management generally occurs at the plant community level. The success of an IWM program will greatly influence weeds at the ecosystem level.

Annual plants germinate, emerge, grow, reproduce and then die. The ability to produce seeds to ensure the next generation is critical for the plant species to remain part of the plant community in a field.
Key Points

- Number of weed seeds in the soil is in constant change as seeds decay, seeds germinate, and new seeds are added.
- Emergence periods differ by weed species and can be as short as four- to five-weeks for some species, while others will continue to emerge over three- to four-months.
- Cover crop residues can influence soil temperatures and temperature fluctuations, and reduce seed exposure to light, all which can prevent cues required for dormancy or germination to be affected.
- Knowing the germination period for a weed species can allow farmers to target management practices to increase the likelihood of controlling weed seedlings.

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Chapter 4: Weed Scouting and Mapping

Annie Klodd

Summary

Scouting is central to understanding the weed populations in a field, which enables targeted and efficient management. This chapter discusses the benefits of scouting, conventional procedures for scouting and mapping weeds, and emerging technologies to improve weed scouting.

Introduction

Scouting for weeds was once a commonplace practice, but its habitual use has decreased in modern agronomic production. Simpler weed management, aided by effective herbicides and herbicide-resistant crop, may have led to this decrease in scouting. Scouting is the only way to identify the weed species present, if they are at a stage that can be controlled with herbicides or cultivation, and the severity of the infestations. This information is important for several reasons:

• Many weed species are only effectively controlled when they are small. Timely scouting confirms the presence of small, susceptible weed seedlings.

• Herbicide programs should take into account the weed species present. Some herbicides, such as glyphosate, are effective for a wide range of species, while other herbicides, such as carfentrazone (Aim®), are highly effective on only a few species.

• Detecting weeds early means herbicides can be applied before the entire field is infested, reducing weed control costs.

Tools Needed for Productive Weed Scouting

Several tools and equipment aid the weed scouting process. These tools include a clipboard with scouting forms, field maps and field history information, hand lens, weed identification references, camera, trowel, knife, bags for samples, quadrat (1 square foot or larger) or tape measure, pencils, and markers. As smartphones and tablets have become more common, some farms and Ag companies use sophisticated scouting software and apps. Global Positioning System (GPS) units can mark weed infestation locations, and monitor them over time to determine the effectiveness of
weed management programs. In the near future, Unmanned Aerial Vehicles (UAVs, commonly called drones) use may become typical, both for scouting for weeds, and other activities that collect field information.

**Scouting Procedure**

The overall goal of an effective weed scouting program is to observe weeds present in a field to understand what weed populations can affect the crop. Data collected through scouting includes existing weed species, population sizes, life cycles, growth stage and size, and distribution throughout the field. For a thorough scouting, choose several sample areas. Each sample area should represent no more than five acres, so sample enough areas for an accurate count of the various weeds present in the whole field. For example, in a 50 acre field, select 10 sampling areas that are well spread out. They could be randomly selected, or they could be distributed a certain distance apart in order to ensure that all sections of the field are covered. At each sampling area, walk 100 feet and record weed species present, growth stage and height, and life cycle (summer annual, winter annual, or perennial). Next, record the severity of the infestation. If a large infestation is encountered within that transect, count the number of weeds found in 10 feet of row. For small infestations, count the number over 100 feet of row.

In many cases, weed infestations cluster in a certain area of the field. In these cases, it is possible that crop scouts walking random transects could miss an important weed population. Various scouting patterns (e.g. zig-zag, “M”- or “U”-shapes, and grid) could be used during the season in order to accurately sample weed populations and to verify if they are increasing or decreasing, if there is a future risk from problem weeds left uncontrolled, and if new species are invading. Walking different patterns in the field with each visit will help increase the likelihood of spotting localized infestations. Walking a higher number of areas per field also improves precision. UAV technology is also being tested for its ability to identify weed clusters remotely (see Aerial Weed Scouting, below).

**When to Scout for Weeds**

There are many common weed species that emerge in the summer and fall, and we recommend scouting early and often to target them effectively. This is especially important in no-till fields where an early preplant herbicide (“burndown”) may be applied. Continue scouting after the crop is harvested until the killing frost. In most cases, three or four times per season is adequate. Specific times vary among fields, but scouting in a timely fashion allows effective control options and assessment (Figure 4.1).
Scouting identifies the presence of weed species and helps direct their control. For many weed species, control at the seedling stage is critical, as many herbicides have the greatest effect on seedlings and lose efficacy as the plants mature, the same is true for mechanical weed control. Regular scouting throughout the season helps keep tabs on weed populations as they emerge and appropriate action can be taken before the infestations become severe. An example of weed emergence patterns can be found in Figure 4.2, and additional information on weed emergence patterns can be found in Chapter 3: Weed Emergence, Seedbank Dynamics, and Weed Communities.
Integrated Weed Management

**Preplant and early postemergence.** Scouting early allows farmers to evaluate the effectiveness of the preplant herbicides or preplant tillage used, and if necessary, take action before the crop is planted. This is important particularly in no-till fields requiring a preplant herbicide to control winter annual weeds. Scouting no-till fields early allows the applicator to cater the herbicide(s) to specific weed populations, ensure applications are made while weeds are at a susceptible stage, and spray before winter annual weeds flower and produce seeds. Scouting shortly after planting also helps the farmer to evaluate the preemergence herbicide's efficacy, and take action while escaped weeds are small and susceptible.

Postemergence herbicides are usually most effective when weeds are young and actively growing. The amount of control with these herbicides will vary due to differences in weed species, growth stages, weather conditions, and herbicide application method. Many postemergence herbicides work best on weeds less than 4 inches tall. To select the best possible herbicide and apply it at the optimum time to maximize control, the manager needs to be able to identify weed seedlings when they are small.

**Mid-season weed and crop survey.** Effective scouting following crop emergence determines whether further management is needed such as rotary hoeing, cultivation, or postemergence herbicides, and helps farmers maintain the critical weed-free period of crop growth. The critical weed-free period is the time the crop needs to be free of weeds to show no detrimental effect on yield. It includes the weeks following crop
emergence until the crop has formed a dense canopy shading out any additional emerging weeds.

**Following all weed control treatments.** Throughout the season, scouting should be done seven to ten days after any weed control treatment, such as herbicide application, tillage, or cultivation. Scouting can check the success of the treatment, record any new weeds that have emerged, and record any crop injury that may have occurred from the herbicide. At this time, resistant weeds and weed species shifts will start to become evident if they are not controlled by the herbicides.

**Late or final weed survey.** Harvest time weed scouting is important for several reasons. If a problematic weed species is located prior to harvesting, and is too dense to be manually removed, the farmer can avoid harvesting those patches and prevent additional spread of seeds. This prevents harvest delays and the spread of weed seeds by equipment due to a heavily infested field. Scouting before harvest can help determine if an herbicide is needed as a harvest aid. Harvest time scouting can allow for assessment of yearly weed management strategies as well as anticipate what weeds may be present the following season based on the surviving weed populations.

**Scouting for Herbicide-Resistant Weeds**
Weeds resistant to certain herbicide modes of action need to be identified. Look for species that are known to have herbicide-resistant populations in the region or surrounding counties. While this scouting procedure includes watching for weeds that have survived herbicide applications, the manager must keep in mind that the failure of an herbicide treatment on a weed does not necessarily mean that it is an herbicide-
resistant weed is present. Many factors must be considered before deeming that the species is resistant.

Signs that a weed population in the field may be herbicide-resistant include:
1) A spreading area of a single weed species that gets larger over time
2) Failure of a usually effective herbicide application to control a single species, especially if the weeds surrounding those were successfully controlled.
3) Individuals within a species that survived an effective herbicide mode of action, and some that did not. This could indicate that some plants of that species in the field are resistant, while others are not.

Detailed criteria for determining herbicide resistance can be found at http://hracglobal.com/herbicide-resistance/confirming-resistance. The website www.weedscience.org provides up-to-date and thorough information about resistant weeds in each state.

**Aerial Weed Scouting with Unmanned Aerial Vehicles**

Aerial remote sensing of weeds via UAVs and satellite imagery has gained increased interest. The goal of aerial weed scouting is to sense the locations of weeds remotely and in a short amount of time, gathering a more robust, precise weed map than would be feasible with traditional scouting alone. Detailed aerial weed maps may enable applicators to direct herbicide applications to specific areas, potentially saving time and money (Pena et al. 2015). UAV technologies are still in development, and there is still much to learn about how to accurately scout weeds with UAVs before these methods are widely marketed to the public for weed-specific applications (Four Seasons Crop Care, personal communication). UAVs use multispectral cameras to capture differences in in field vegetation. As the UAV flies over the field, the camera creates an image of the colors emitted from the plants in the field. Depending on the quality of the image and several other factors, appropriate software may be able to distinguish weeds from crops based on subtle differences in pigmentation and growth patterns. For example, an image showing green vegetation between crop rows, or growing when no crop is in the field, may indicate weeds. As the technology advances, researchers hope to sense weeds growing within the crop based on color differences among plant species.
The ability of this technology to distinguish weeds from crops and identify weed species is affected by many factors including camera type, UAV model, altitude, time in the season, weather, and size of the plants (Pena et al. 2015). Weeds need to be identified as seedlings for optimal herbicide control, and aerial sensing is more difficult on smaller weeds (Pena et al. 2015). However, some technologies identify the presence of small seedlings, and direct scouting efforts to certain areas (even if they are not able to pinpoint species). Another limitation is the time required to download data and create usable information. Researchers are currently working to improve the technology for weed management; however, UAV technology should not replace walking the field. It can direct scouting efforts to problems in the field, and provide a relative estimate of weed severity throughout the field, but physically walking fields and observing the status of the weeds and crop is still a productive and necessary effort.

Key Points

- Scouting should be conducted before planting, after herbicide applications, and at or after harvest time.
- ID and record all weeds found and look for trends or new species and infestations.

References

Chapter 5: Concept of Weed Thresholds

Mark VanGessel

Summary

Knowing when weed density (or weed biomass) is at a level that can reduce crop yield, quality, or interfere with harvest efficiency is needed to prevent crop yield loss. Weed biomass is a combination of the number of weeds and when they emerged; with earlier emerging weeds having more biomass. Not all weeds need to be controlled to achieve maximum yield, but the number of weeds or weed biomass must be low enough to not reduce yield or interfere with harvest. Recent emphasis on thresholds have shifted from eliminating the effect of weeds on crop yield to reducing weed seed production.

Introduction

Weeds reduce crop yields either directly by competing for moisture, nutrients, light, and carbon dioxide (CO₂); or indirectly by harboring other pests, interfering with harvest, contributing to foreign matter in the harvested crop, or slowing crop dry-down. Farmers spend time and money trying to control weeds, often spending more than necessary. It is seldom necessary to control all the weeds in a field to achieve maximum crop yields. The goal is to keep weed density and weed biomass at a level that will not affect yield. Methods such as cover crops, mechanical weed control, and/or herbicides are used early in the season until the crop is established enough to outcompete the weeds. A healthy, vigorous crop canopy outcompetes weeds, keeping them in check and is the best tool a farmer possesses for maintaining weed control until crop maturity.

Many factors will influence the severity of weed competition including the weed species, density, emergence timing, crop management (e.g. row spacing, varietal differences), environmental conditions, fertility, and soil moisture levels. For instance, common cocklebur had a greater effect on soybean yield when moisture levels were high compared to moisture-stressed conditions (Mortensen and Coble 1989) (Figure 5.1). Trials conducted under long-term organic systems suggest that organic cropping systems may be able to tolerate a greater abundance of weeds than conventional systems (Ryan et al. 2009). The specific factors causing the potential differences in these two systems have not yet been investigated.
Weed Density Threshold

Determining when weed management strategies should be implemented to control emerged weeds is based on two concepts: weed density or critical weed-free period. Weed density are based on the principle that weeds below a certain density or biomass level will not reduce crop yields; while weeds above this threshold will begin to reduce yield. Weed density thresholds analyze weed species and density and calculates an expected crop yield loss. Models are available to determine the yield loss potential, cost of management, and expected economic return to help a farmer or crop advisor to select the best management options. Weed density thresholds have been studied extensively, but results can be difficult to interpret because of the complex interactions that are involved. In Table 5.1 the expected yield loss from various weed species differ from two extension publications. In Maryland, only 20 common lambsquarters in 100 ft² can caused a 10% corn yield reduction, while 60 plants are required for a similar yield loss in Illinois. This is presumably due to finer-textured soils in Illinois that are better adapted to retain soil moisture, compared to coarse-textured soils commonly found in Maryland.

Table 5.1. Number of weeds per 40 feet of row* expected to cause 10% yield in corn**.

<table>
<thead>
<tr>
<th>Weed</th>
<th>Maryland</th>
<th>Illinois</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual grasses</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Common cocklebur</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Common lambsquarters</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>Jimsonweed</td>
<td>12</td>
<td>32</td>
</tr>
<tr>
<td>Morningglory</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Pigweed</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>Smartweed</td>
<td>20</td>
<td>32</td>
</tr>
<tr>
<td>Velvetleaf</td>
<td>12</td>
<td>40</td>
</tr>
</tbody>
</table>

*40 feet of row (30-inch rows) is 100 ft²
**Data based on information from Maryland Cooperative Extension values and Illinois Cooperative Extension values

Figure 5.1. Soybean yield loss due to weed competition under high or low soil moisture conditions. (Source: Mortensen and Coble 1989)
Critical Weed-Free Period

Maintaining the crop weed free for a certain time period while the crop gets established and reaches a stage it can outcompete or shade out later weeds is known as the critical weed-free period (Figure 5.2). During a few weeks early in the season weeds can compete with the crop and the weed competition has little to no impact on final yield. Likewise, there is a stage later in the season when weeds can emerge and grow without causing a yield reduction. Late emerging weeds will not cause yield reduction for three reasons:

1. the crop has developed (or will develop) a dense crop canopy to suppress or outcompete any weeds;
2. before harvest the weeds do not have sufficient time to compete with the crop before harvest; or
3. it is too late in the season for the weeds of concern to emerge.

A number of factors determine the length of the weed-free period, many of the same factors that influence the outcome of weed thresholds (Table 5.1 and Figure 5.3). Critical weed-free period is also based on the assumption that there are no weeds present at time of planting, whether the field was tilled before planting or an herbicide was used to eliminate emerged weeds.

Many farmers are using critical weed-free periods often without realizing it. Farmers may 1.) use a cover crop or soil-applied herbicide to provide early-season weed suppression and then use a postemergence weed control tactic such as cultivation or a postemergence herbicide; 2.) apply an early-postemergence herbicide that provides residual control; or 3.) include two to three cultivations with the final cultivation late enough in the season that later emerging weeds do not reduce crop yield.
Figure 5.2. Timing of weed control practices on critical weed-free periods.
A. the period of time that a crop should be weed free to achieve maximum yields;
B. common situation of early-season weed control with a preemergence herbicide, cover crop, or stale seedbed; followed by a postemergence (POST) herbicide or cultivation;
C. poor early-season weed control with weeds becoming too large for effective control; and
D. cultivation or postemergence herbicide applied too early with crop canopy unable to suppress later emerging weeds.
Critical weed-free period is based on the principle that 100% weed control is not necessary to protect the crop yield. However, most of the research on critical weed-free period has examined yield loss and may not have accounted for foreign matter in the harvested crop, ease of harvest, or the impact of late emerging weeds on weed seed production.

Spraying Postemergence Herbicides by the Calendar

Crop fields need to be scouted and treated before weed density or biomass are at a level to reduce yield, but also when weeds are small and susceptible. If fields are not scouted, research conducted in the Mid-Atlantic region has demonstrated that soybeans treated with a postemergence herbicide at the V-4 stage provided excellent weed control and allowed the soybean canopy to outcompete later-emerging weed species. The results were similar for both full-season no-till and conventional tillage soybeans. The timing for double-cropped soybeans (following winter wheat) were less consistent, but in most years, an herbicide application at the V-5 stage did not reduce yields (VanGessel et al. 2000, 2001).

Generally, corn yield is not reduced if weeds are removed at the V-4 stage. The application window for corn is wider when weed densities are lower, but this application timing coincides with weeds that are small enough for effective control, while still late enough in the season that the corn can outcompete most later emerging weeds (Gower et al. 2002, 2003; Myers et al. 2005).

In addition, many trials conducted by universities in the region have found a postemergence herbicide application at four weeks after planting (which coincides with the V-4 stage for corn and soybeans) has provided the most consistent weed control while maintaining optimum yields. Palmer amaranth and waterhemp are two weed species that are very competitive, grow very rapidly, and will germinate throughout the summer. As a result, these two species often require the postemergence treatment to include an effective residual herbicide to lengthen the weed-free period to eliminate the need for additional treatment needed.
Preliminary data at the University of Delaware and Virginia Tech have shown the importance of application timing in small grains as well. Herbicides applied in the fall when wheat has two to three tillers prevented yield loss. However, delaying the small grain herbicides until late spring resulted in yield reductions. Winter wheat is a competitive crop and requires a relatively short weed-free period to prevent yield reduction.

**Surviving Weeds May Contribute To The Seedbank**

While weeds emerging after the critical weed-free period do not affect yields, they often mature and produce seeds. However, the seed number is much lower than plants that emerge shortly after planting the crop. If zero seed production is desired, the critical weed-free period is much longer to prevent later emerging weeds from producing viable seeds. Currently, there is no regional research to provide guidance on how much longer the critical weed-free period needs to be extended to prevent the production of viable weed seeds (see Chapter 14: Harvest Weed Seed Control for more detail).

In the southern regions of the United States, the first killing frost is late enough to allow weeds that have not begun to flower at harvest to resume growing and produce significant number of seeds. In some situations, farmers are advised to control these weeds with tillage or herbicides to prevent seed production. In the Mid-Atlantic region, this maybe an issue for early harvested corn or silage corn.

**Key Points**

- Not all weed species have the same effect on yield loss
- The environment has a large impact on the outcome of weed competition
- Achieving a critical weed-free period requires:
  - effective early-season weed control
  - ability to achieve a high level of weed control once weeds have emerged
  - may require more that one weed control operation once weeds have emerged or incorporating a residual herbicide with a postemergence herbicide
- A vigorous crop canopy is an important component to late-season weed management

If weeds emerge after corn is established, they do not compete as well or produce as many seeds. Ten barnyardgrass seedlings emerging from planting up to the 3-leaf corn stage produced 1,350 to 3,210 seeds ft² while seedlings emerging after the 4-leaf corn stage produced 110 to 260 seeds ft² (Bosnic and Swanton 1997).
References

Chapter 6: Prevention of Weeds

Michael Flessner

Summary

Keeping weeds from entering a field or spreading within a field is critical to successful integrated weed management. Various tactics are employed to achieve this goal, including cleaning equipment, planting weed-free seed, and controlling weeds prior to seed production, among others.

Introduction

Preventing weeds from entering a field or spreading within a field is critical to successful integrated weed management. However, prevention can be difficult because weeds are well adapted for spread. Faithful prevention practices will reduce the weed population over time, making this and other management tactics easier and cheaper. Neglecting prevention forces managers to battle weeds after infestations, treating symptoms rather than underlying problems.

Weed prevention is a job that is never finished. Managing weeds both in-crop and between crops is key to successful prevention. The spread of weeds by processes such as wind and movement by birds or animals is difficult to manage. This chapter will focus on seed dispersal by human activities and how to manage such spread. The following is a list of prevention practices and tactics.

Weed Prevention Practices

Planting

Plant certified, weed-free crop seed. Planting “bin-run” or saved crop seed contaminated with weed seeds places weed seeds directly in the crop row, spreads weeds within and between fields, and may increase establishment by increased seed-to-soil contact. All of these increase competition with the crop.
During the season

Do not let weeds set seed, especially weeds with high seed production that are capable of rapid infestation, such as Palmer amaranth. Eliminating seed set of Palmer amaranth for one season reduced the number of weeds by over 3-fold in the following season (Flessner et al. 2018).

Ensure weed-free irrigation and drainage waters. When surface irrigating, water can easily spread and introduce weed seeds and other plant parts capable of infestation (Walker 1995).

Harvest

Clean harvest and grain transporting equipment. Remove weed seed and other weedy plant parts from all equipment prior to moving into the next field (Photo 6.1). In particular, harvesters can move weed seeds more than 450 feet from the mother plant resulting in weed spread within and between fields (Shirtliffe and Entz 2005). Models have calculated crop yield losses of more than one third in the area directly behind the harvester, where weed seeds are dispersed at the highest density, compared to areas at the edge of the harvester’s spread pattern (Maxwell and Ghersa 1992).

![Photo 6.1: Cleaned brush mower (left) versus a brush mower covered in dandelion seed (right). (Photo credit: M. Flessner)](image)

Post-harvest weed control

Weeds that emerge as a crop is drying down for harvest or that emerge after harvest may produce viable seed before a killing frost in certain parts of the Mid-
Atlantic region. Preventing these weeds from producing seed reduces weed pressure faced in the following season (see Chapter 14: Harvest Weed Seed Control).

**Practices throughout the year**

There are a number of ways weed seed can enter a particular field. The following are practices and considerations to keep in mind.

- Do not spread weed infested hay, straw, manure, or soil on clean fields.
  - Composting will reduce the number of viable weed seeds. However, weed seeds on the edges of compost piles may survive as they are not subjected to the heat required to kill them. When purchasing compost ensure the source of material does not contain weed seeds.
- Livestock can spread weed seed.
  - Many weed seeds remain viable after passing through the gut of cattle and poultry. If these animals are fed anything that contains viable weed seed or are allowed to graze a weedy field, quarantine the animals for three to seven days (until the seeds completely pass through their digestive systems) before moving them to clean fields.
  - Ensiling will greatly reduce viability of most weed seeds, although it may not be completely eliminated (Crafts and Robbins 1962).
- Control weeds around the farm in areas such as ditches, roadsides, the exterior of structures, and fence lines. Weeds growing in these areas will be a continuous source of field infestation.

**Other weed prevention considerations**

- Crop rotation prevents build-up and domination of weeds common to a particular crop (Walker 1995). A diverse crop rotation increases the number of environmental and management obstacles for weeds (Wortman et al. 2010). See Chapter 10: Cultural Control, for more information.
- Fallow periods in a crop rotation allow weeds to grow without competition and produce weed seed, which can replenish weed seedbanks and cause increased problems for years to come. For example, common lambsquarters has been reported to increase its weed seedbank size 14 fold in a single fallow period (Leguizamon and Roberts 1982).
- Cover crops or smother crops may be used to prevent weed population build-up between cash crops. Care must be taken so that the cover crop does not become a weed itself (Walker 1995). See Chapter 12: Cover Crops for Weed Suppression, for more information.
- Weeds that produce wind-borne seeds, such as thistles or horseweed, should be managed wherever they occur, prior to seed set.
Key Points

- Plant certified, weed-free crop seed.
- Do not let weeds set seed.
- Avoid introducing sources of new weed infestation, such as hay, manure, and compost.
- Clean equipment to prevent weed seed and propagule spread, particularly harvest equipment.
- Rotate crops and avoid fallow periods.
- Control weeds around the farm in areas such as ditches, roadsides, and fence lines.

References


Chapter 7: Weed Resistance to Herbicides

Thierry Besançon

Summary

Herbicide-resistant weed populations are evolving rapidly worldwide and represent the greatest challenge to current weed management strategies. By exerting intense selection pressure on weed populations, repeated overuse of certain herbicides has selected for herbicide-resistant biotypes. Understanding its mechanisms and knowing how resistance develops and spreads allows farmers to detect the early warning signs of herbicide resistance, take appropriate actions to control suspected plants, and implement strategies to avoid or delay the onset of herbicide resistance.

Introduction

Repeated use of herbicides targeting the same plant physiological processes has led to the selection of plants that can naturally survive applications of these herbicides (Vencill et al. 2012).

Herbicides exert a tremendous selection pressure on weeds by killing susceptible individuals, but allowing naturally resistant individuals to survive and reproduce. Currently, herbicide resistance has been reported in 252 species of weeds worldwide, affecting 92 crops in 69 countries. Overall, weeds have evolved resistance to 23 of the 26 known herbicide mechanisms of action for a total of 163 different herbicides (Heap 2017). The greatest number of herbicide-resistant weed species is reported for the acetolactate synthase (ALS)-inhibitor, triazine, and acetyl CoA carboxylase (ACCase)-inhibitor herbicides (Figure 7.1). The continual development spread of plants that evolved herbicide resistance within some weed species poses a direct threat to the sustainability and the long-term survival of current cropping systems. The presence of herbicide-resistant weeds requires substantial changes in weed and crop management practices, increases the cost of weed control, and reduces the number of viable herbicide options. Therefore, a good understanding of the origin and underlying causes of herbicide resistance is needed to develop herbicide resistance avoidance strategies and preserve current management tools still effective at controlling weeds, including those that have evolved herbicide resistance.
How Does Herbicide Resistance Develop?

Herbicide resistance is the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type (WSSA 1998). In simple terms, an herbicide no longer controls a weed population as it once did. While susceptible plants within a weed population will be killed, rare plants that naturally developed a genetic resistance to a specific herbicide will escape and reproduce. This is called selection pressure as the herbicide is selecting for plants that are fitted to survive this herbicide. If this process goes on for several weed generations, the populations of the herbicide-resistant weed biotype will progressively increase until a noticeable portion of the weed population is no longer controlled by the herbicide. That is usually when farmers begin to realize that an herbicide once effective at controlling various weed species does not provide anymore the expected level of control for a given weed species.

Mechanisms of Herbicide Resistance

Several mechanisms of herbicide resistance have been identified in various weed species, including target-site and non-target site resistance. Weeds
may evolve resistance to herbicides through target-site resistance. The target-site is the specific location within the plant where an herbicide acts to disrupt a particular plant process or function (mode of action). If the molecular structure of the target site, usually an enzyme, is altered, then herbicide cannot longer bind to its site of action and interfere with plant physiological processes. Change in the conformation of the site of action is considered as the primary mechanism of resistance for herbicides that are inhibiting the enzymatic activity of acetyl-CoA carboxylase (ACC inhibitors), protoporphyrinogen oxidase (PPO inhibitors), and protoporphyrinogen oxidase (PPO inhibitors) (Powles and Preston 2006). This is also the mechanism involved with resistance to herbicides inhibiting cell mitosis (dinitroanilines) or photosynthesis by blocking the electron flow in the photosystem II. As of the end of 2017, there were 159 weed species resistant to various ALS-inhibiting herbicides, 73 to PSII-inhibitors, 48 to ACCase-inhibitors, 13 to PPO-inhibitors, and 12 to mitotic-inhibitors (Heap 2017). Target-site resistance can also be caused by a higher level of enzyme expression in resistant plants. In the case of glyphosate-resistant Palmer amaranth, research has shown that resistant plants were producing more copies of the EPSP synthase enzyme targeted by glyphosate than susceptible plants. Thus, at the labelled rate, the number of glyphosate molecules taken up by the plant will not be sufficient to bind to all enzyme copies, and some will keep performing their physiological activity. By increasing its number of EPSP synthase copies, the plant survives a glyphosate rate that would otherwise be lethal to susceptible plants.

Non-target-site resistance is another mechanism through which plants can develop resistance to herbicides without involving the herbicide active site in the plant. The plant can enhance its metabolic activity and increase the detoxification of herbicide active ingredient. It can reduce the absorption of herbicide active ingredient or limit the quantity of herbicide that will reach to the site of action. It can also sequester herbicide within an inactive cellular site. Resistance mechanisms involved in non-target-site may be the expression of natural enhanced tolerance to environmental stresses.

Selection of Herbicide-Resistant Biotypes

Although various environmental, biological, and human factors will determine the onset of herbicide resistance and the rapidity at which it will spread, the way herbicides are used for controlling weeds is the most important factor leading to the evolution of herbicide resistance (Norsworthy et al. 2012). Repetitive use of a single herbicide or a group of herbicides with the same mechanism of action leads to the selection of herbicide-resistant weeds. Plants with genetic adaptations that give them the ability to withstand a specific herbicide are originally present within a weed population at a low frequency. When this herbicide is applied, susceptible plants will be controlled, but resistant plants will survive, grow, and ultimately produce seeds that will be contribute to the spread of herbicide resistance. This selection process continues
when that same herbicide is repeatedly applied, allowing the number of resistant individuals to gradually increase until the majority of the plants within a weed population is herbicide-resistant. For example, research has shown that a horseweed population from the Mid-Atlantic region evolved resistance to glyphosate after three years of consecutive glyphosate applications on glyphosate-resistant soybeans (VanGessel 2001).

Furthermore, the use of reduced herbicides rates can also be a contributing factor to the evolution of herbicide-resistant weeds. For instance, diclofop (Hoelon®) applied below the labelled rate has been a major factor to the development of diclofop-resistant rigid ryegrass in an Australian wheat field (Manalil et al. 2011). Herbicide susceptibility varies among individuals within a weed population, allowing some plants to survive when exposed to an application at below-label rates. It has been hypothesized that reduced herbicide rates may allow plants with low or intermediate levels of resistance to survive. Consistently spraying herbicides at reduced rates results in the accumulation of minor resistance genes. Over time, cross-pollination contributes to the recombination of these genes, leading to plants with higher levels of herbicide resistance. Reduced rates are not always the result of a weed management strategy, but can also be linked with herbicide chemistry or formulation. For example, emanations from highly volatile herbicides or slow degradation of soil-applied herbicides expose plants to sub-lethal herbicide rates and may select for herbicide resistance as previously discussed. Likewise, reduced rates can result from herbicide applied on plants larger or at a more advance growth stage than recommended by the label. Similarly, large crop cover, inappropriate mixing, or inaccurate calibration result in insufficient spray coverage and reduce the effective weed control rate. Therefore, the use of full-labeled rate is key to prevent evolving of herbicide resistance and should be accompanied with proper weed scouting and sprayer calibration (see Chapter 4: Weed Scouting and Mapping).

Factors Affecting Resistance Development

Herbicide chemistry and behavior in soil or plant play an important role in selecting for herbicide-resistant plants. Herbicides that provide greater weed control efficacy eliminate a greater portion of herbicide-susceptible plants within a weed population. Since only plants that are herbicide-resistant will survive and reproduce, resistance is more likely to develop in weeds that are highly susceptible to a specific herbicide.
Similarly, herbicides that degrade slowly will exert a greater selection pressure because weeds are exposed to the herbicide for a longer period of time. Susceptible seedlings emerging after the use herbicide that has no or short residual activity will survive and reproduce, replenishing the soil seedbank with herbicide-susceptible seeds. On the other hand, susceptible seedlings emerging after the use of a long-residual herbicide will still be exposed to herbicides, and only resistant biotypes will survive and reproduce.

Herbicides that are targeting a single mechanism of action will more likely select for herbicide-resistant weeds as compared to herbicides that are interfering with multiple processes in the plant. For example, ALS-inhibitor herbicides (Group 2) specifically target the acetolactate synthase, and any conformation change to this enzyme can confer resistance to the various active ingredients belonging this herbicide family. On the other hand, chloroacetamide herbicides (Group 15) are thought to interact with various enzymes involved in the biosynthesis of very long chain fatty acids. Targeting multiple mechanisms of action may explain why resistance to chloroacetamide herbicides is relatively rare with only five known case of resistant weed whereas resistance to ALS-inhibitors has been confirmed for 160 species worldwide.

Biology and genetics of weed species are also important factors in herbicide resistance development. The frequency at which resistance occurs in a weed population before herbicides are applied will determine the required time for herbicide resistance to evolve. For example, resistance will spread faster with a frequency of 1 resistant plant in 100,000 than in 10,000,000 total plants. Weed species with greater genetic diversity more likely harbor genes conferring resistance to a specific herbicide. For example, weeds belonging to the *Amaranthus* genus (or pigweeds) appear to have considerable genetic diversity and some species have developed resistance up to six herbicide modes of action (Heap 2017). Cross pollination and production of a large number of seeds enhance the potential for dispersal of herbicide resistance. For example, Palmer amaranth male and female flowers are on separate plants, making cross pollination necessary to the production of seeds. Transfer of glyphosate-resistance through pollen dispersal has been observed for this species between glyphosate-resistant male and female plants.
glyphosate-susceptible female plants that were 1,000 feet apart from each other (Sosnoskie et al. 2012). Additionally, Palmer amaranth seed production can average 500,000 seeds per plants in the absence of plant competition, allowing quick spread of glyphosate-resistance.

The size of the weed population is also a major factor contributing to the onset of herbicide resistance. To a greater number of plants exposed to herbicide corresponds a higher risk of selecting for resistance and increasing the frequency of rare resistance genes within the population of a specific weed species (Gressel and Levy 2006). Therefore, preventing the buildup of a large number of plants and the replenishment of the weed soil seedbank is a key component in herbicide-resistance management.

Types of Herbicide Resistance

Cross resistance occurs when a weed develops resistance to two or more herbicides that act at the same site of action (Vencill et al. 2012). These herbicides can belong to the same or different chemical family. For instance, a single point mutation in the enzyme acetolactate synthase (ALS) of common ragweed may provide resistance to chlorimuron (Classic®) and cloransulam (FirstRate®). These herbicides belong to two different chemical families, but have the same mechanism of action (Figure 7.2).

Multiple resistance refers to a weed that is resistant to several herbicides with different mechanisms of action (Powles and Preston 1995). This type of resistance may be the result of two or more different resistance mechanisms.

Figure 7.2. Example of cross-resistance in common ragweed. Chlorimuron is active ingredient in Classic®; cloransulam is active ingredient in FirstRate® and both herbicides are acetolactate synthase-inhibiting herbicides (or Group 2). (Source: Weed Science Society of America, 2017)
within the same plant. For example, imagine that a farmer applies FirstRate®, an ALS-inhibitor herbicide (group 2), to control common ragweed (Figure 7.3). The repeated use of FirstRate® unintentionally selects for an ALS-resistant biotype (shown in black) which will become predominant in the common ragweed population, and preventing effective ragweed control. The farmer switches to Roundup®, a 5-enolpyruvylshikimate-3-phosphate (EPSP) synthase inhibitor (group 9), and uses it for several continuous years. Continued use of Roundup® selects for plants resistant to group 9 herbicides within a population that is already resistant to group 2. Ultimately, common ragweed population has evolved towards multiple herbicide resistance as it is made of plants that are resistant to both group 2 and group 9 herbicides.

![Diagram showing the process of multiple resistance development in common ragweed](Image)

Figure 7.3. Example of multiple resistance in common ragweed. ALS-resistance are biotypes resistant to acetolactate synthase-inhibiting herbicides (or Group 2, i.e. Classic® or FirstRate®). Glyphosate is the active ingredient in Roundup® and is a Group 9 herbicide. (Source: Weed Science Society of America, 2017)

**Weed Species Shifts and Weed Resistance**

Weed species shift is a change over time in the relative abundance of the various species that form a weed population. Within the weed population, the different species are not equally affected when applying a specific herbicide. Some species can be fully eliminated when others are only partially or not controlled at all. Recurrent use of the same herbicide causes weed population to shift towards species that are not vulnerable to this herbicide. For example, the continued use of broadleaf herbicide 2,4-D in cereal grain crops will eventually lead to the elimination of susceptible broadleaf weeds. Grassy weeds that are tolerant to 2,4-D will survive and multiply, eventually dominating the weed population (Figure 7.4). Weed species shifts are not necessarily
driven by herbicide use but may also be the result of other agronomic practices such as tillage, crop rotation, or nonchemical weed control techniques.

Figure 7.4: Example of a weed species shift due to 2,4-D application and grass tolerance to 2,4-D (Source: Weed Science Society of America, 2017).

Herbicide resistance presents a different type of weed shift. In contrast to the previously described shift, plants are considered to be initially susceptible to a specific herbicide with the exception of some rare cases. Continued use of this herbicide may select for herbicide-resistant biotypes that will ultimately prevail in the weed population (Figure 7.5). Both grasses and broadleaf weeds may develop herbicide resistance.

Figure 7.5: example of shift caused by glyphosate-resistance in common ragweed.
Spread of Herbicide Resistance

Once established in a field, herbicide-resistant weeds can easily spread and colonize resistance-free fields, whether by pollen, seed or vegetative structures dispersal.

The movement of pollen from herbicide-resistant plants to susceptible plants is an important source of resistance dispersion as cross-pollination will produce seeds that may carry the resistance. If these seeds ripen and replenish the soil seedbank, the resulting emerging plants may survive herbicide application and in turn increase resistance dissemination through seed production. The risk of resistance spreading is higher for cross-pollinating weeds, such as pigweed, than for self-pollinating species, such as grasses. Outcrossing distance is determined by the size of pollen grains, the wind velocity, the ability of weeds to attract pollinators, the amount of pollen available for dispersal, and the length of time during which pollen is viable for pollination. The only way farmers can prevent the spread of pollen-mediated herbicide resistance is to eliminate suspected resistant weed species from the field and surrounding areas prior to flowering.

Seeds also are an important herbicide-resistance dispersion route, especially because seeds can be transported by agricultural equipment. Dispersal can occur through mowing, tilling, or harvesting equipment, to which seeds can easily stick. Combines are a significant source of seed spread because crop harvest usually occurs at the same time as weed seed maturation. Weeds and crops are harvested simultaneously, and harvesters’ mechanical complexity makes them harder to clean than other pieces of farm equipment. Resistant seeds also can be dispersed through farming activities such as irrigation, contaminated crop seeds or manure used for fertilization, and the transport of hay or agricultural by-products. Human-mediated actions disseminate herbicide-resistant weed seeds over a greater distance than animal-mediated actions or environmental seed transport (Figure 7.6). Birds or grazing animals that consume seeds in fields are an underestimated source of seed dispersal as consumed seeds may not completely degrade during digestion, and remain viable even after passing through the animal. Finally, wind is the natural mean of dispersal for some weed seeds. If a weed developed resistance to a specific herbicide, seeds from the resistant plants can be carried over long distance by the wind, and contribute to the dissemination of herbicide resistance. For example, horseweed seeds are extremely light, resembling those of dandelions, allowing them to be transported by the wind. In some situations, seeds can be transported to higher altitudes by vertical winds and travel long distances, spreading resistant weeds hundreds of miles away from their points of origin (Shields et al. 2006).
Movement of vegetative structures such as tubers, rhizomes, or portions of stems from which a plant can be regenerated also contributes to the diffusion of herbicide resistance. However, distance of herbicide resistance spread is usually shorter than for seed-mediated transport since vegetative structures are mostly moved within a field as a result of tillage operations.

**Resistance Avoidance Strategies**

Herbicide resistance will evolve in a weed population if two conditions are satisfied:
1. Plants with a naturally occurring mutation that confers resistance to a specific herbicide are already present in the weed population, and
2. These plants should be subjected to intense selection pressure by using the herbicide to which they are resistant.

It is impossible for farmers to know about resistance mutations within the plants, until they start noticing inadequate weed control. This is because resistance traits are not visible on the plant. Therefore, preventing resistance issues requires reducing the opportunities for resistant individuals to survive and reproduce.

Herbicides should be wisely used and rotated to prevent the selection of herbicide-resistant plants. Rotating effective herbicide modes of action, either by applying multiple modes of action within a given crop or by rotating crops between two cropping seasons, is the most important factor to reduce weed selection pressure imposed by herbicide applications. The combination of different modes of action...
action, through mixing or sequential applications, can efficiently control plants that are naturally resistant to one specific mode of action, and delay the onset of herbicide resistance. The use of full labeled herbicide rates is also recommended to prevent the selection of plants that would survive exposure to a sub-lethal rate. It is equally important to follow recommendations about the size of the weeds when applying a postemergence herbicide. Spraying plants taller than the maximum recommended size reduces the amount of herbicide reaching the plant, and can result in the application of a sub-lethal rate. Non-uniform distribution of the spray solution caused by improper sprayer calibration or excessive weed density may also decrease efficacy and select plants that can survive a sub-lethal herbicide dose.

Using cultural practices to control weeds or increase crop competiveness with weeds reduces reliance on sole herbicides for managing weeds. Different strategies may be implemented to promote rapid development of crop canopy and to reach canopy closure as quickly as possible. Variety selection, sowing time, rate and depth, row spacing and orientation, crop fertilization, irrigation, and pest control are elements that influence early canopy closure and can improve crop’s competitive ability with weeds (see Chapter 10: Cultural Control). Cover crops and soil cultivation can also stimulate crop competiveness (see Chapter 12: Cover Crops for Weed Suppression and Chapter 13: Pre- and Post-Plant Mechanical Weed Control). All these cultural practices alone or combined may help to reduce weed emergence and growth.

Other key components of any resistance avoidance strategy include the planting of crop seeds free of weeds and the control of weeds in field borders. Maintaining the crop free of weeds as long as possible by using nonselective herbicides for preplant applications and preemergence herbicides for residual control is also an important strategy to delay the outbreak of herbicide-resistant weeds.

Finally, the rapid detection of weed resistance is crucial and should rely on efficient weed scouting techniques (see Chapter 4: Weed Scouting and Mapping). Signs that a weed population in a field may be herbicide-resistant include the following:

- Poor herbicide performance on one weed species but not others, even though the herbicide is known to be efficient at controlling this species.
- Spotty distribution within the field of plants that survived the application of an herbicide that should have controlled them.
- Within a weed species, a majority of plants have been controlled with an efficient herbicide but some have escaped control.

All possible actions should be taken to prevent seed production of plants suspected of being herbicide-resistant. Options include hand weeding, use of an efficient herbicide, or mechanical destruction of all surviving plants within the affected areas.
Key Points

- Overuse of a single herbicide mode of action may select for individual plants within a weed population that can survive the labelled rate of this herbicide that would otherwise be lethal on susceptible plants.
- Resistance can be caused by structural modification of the herbicide target within the plant (target-site) or by other metabolic or exclusion mechanisms not related to the target (non-target-site).
- Resistance will result in the dominance of one species to the exclusion of other weeds.
- Environmental factors and human-related activities can help resistant weeds to spread over large distances that can sometimes exceed hundreds of miles.
- The wise use of herbicides, the diversification of weed management approaches, and the early detection of suspected resistant weeds are key strategies in preventing the development and spread of herbicide resistance.

References


Chapter 8: Chemical Control: Herbicide Management Issues

Dwight Lingenfelter

Summary

Herbicides are crop-protecting chemicals used to kill weedy plants or interrupt normal plant growth, and can provide a convenient, economical, and effective way to help manage weeds. In most cases, they can be the backbone of many weed management programs. However, they should not be used alone but integrated with effective nonchemical tactics such as tillage, crop rotation, proper soil fertility, or other appropriate management options. Herbicides may not be necessary on some farms or landscapes. If chemical weed control is not utilized, mechanical and cultural control methods then become the priority.

Introduction

Over the past 60 years, synthetic herbicides have been widely adopted as a means to control weeds. Many herbicides control weeds in different types of crops with no or negligible injury to the crop. Furthermore, herbicides allow reduced tillage at planting, earlier seeding dates, and provide additional time for farm tasks and personal life. Due to reduced tillage, soil erosion has been reduced from about 3.5 billion tons in 1938 to 0.96 billion tons in 2012 (USDA NRI Report 2015), thus decreasing the amount of soil entering waterways and improving the nation’s surface water quality. Without herbicide use, no-till agriculture becomes impossible.

However, herbicide use also carries environmental, ecological, and human health risks. It is important to understand the benefits and disadvantages associated with chemical weed control prior to use. Companies spend hundreds of millions of dollars to develop and test herbicides to meet stringent standards set by the U.S. government. The herbicide label is a result of this process and is a legal document designed to maximize weed control and minimize crop injury, environmental damage, and personal injury of those applying the product, as well as any incidental contact of others near the application area.

Herbicide Classification

Herbicides can be categorized in different ways and by certain characteristics. In this publication, herbicides are classified according to: a) mode and site of action; b) application timings and methods; c) weed control spectrum and selectivity; and d) herbicide movement in the weed. Each of these is discussed below.
**Herbicide mode and site of action**

The term “mode of action” refers to the sequence of events from absorption into plants to plant death, or, in other words, how an herbicide works to injure or kill the plant. The specific location the herbicide affects is called the site or mechanism of action. To be effective, herbicides must (1) adequately contact plants, (2) be absorbed by plants, (3) move within the plants to the site of action without being deactivated, and (4) reach toxic levels at the site of action. Understanding herbicide mode of action is helpful in knowing what groups of weeds are controlled, specifying application techniques, diagnosing herbicide injury problems, and preventing herbicide-resistant weeds.

A common method of grouping herbicides is by their modes of action. Although a large number of herbicides are available in the marketplace, several have similar chemical properties and the way they control the weed. Two or more families may have the same mode of action and will be listed under the same group number. Table 8.1 is a simplified list of the common herbicide modes of action groups and example herbicides. For a more extensive list and utility of each refer to the *Mid-Atlantic Field Crop Weed Management Guide*.

<table>
<thead>
<tr>
<th>Mode of action (effect on plant growth)</th>
<th>Site of action</th>
<th>Herbicide group #</th>
<th>Active ingredient</th>
<th>Trade name(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lipid (fatty acid) inhibitor (meristem)</td>
<td>ACCase enzyme</td>
<td>1</td>
<td>clethodim</td>
<td>Select® Assure II®</td>
</tr>
<tr>
<td>Amino acid biosynthesis inhibitor</td>
<td>ALS enzyme</td>
<td>2</td>
<td>chlorimuron</td>
<td>Classic® FirstRate® Pursuit® Resolve®</td>
</tr>
<tr>
<td>Seedling growth inhibitor – root &amp; shoot</td>
<td>Microtubule</td>
<td>3</td>
<td>pendimethalin</td>
<td>Prowl®</td>
</tr>
<tr>
<td>Plant growth regulator</td>
<td>TIR1</td>
<td>4</td>
<td>2,4-D</td>
<td>2,4-D Clarity®</td>
</tr>
<tr>
<td>Photosynthesis inhibitor – mobile</td>
<td>Photosystem II</td>
<td>5</td>
<td>atrazine</td>
<td>atrazine TriCor®</td>
</tr>
<tr>
<td>Amino acid biosynthesis inhibitor</td>
<td>EPSP enzyme</td>
<td>9</td>
<td>glyphosate</td>
<td>Roundup®</td>
</tr>
<tr>
<td>N-metabolism disrupter (contact)</td>
<td>GS enzyme</td>
<td>10</td>
<td>glufosinate</td>
<td>Liberty®</td>
</tr>
<tr>
<td>Cell membrane disrupter (contact)</td>
<td>PPO enzyme</td>
<td>14</td>
<td>flumioxazin</td>
<td>Valor® Reflex® Sharpen®</td>
</tr>
</tbody>
</table>

Table 8.1. Common herbicide mode of action classes and examples
**Herbicide application timings and methods**

**Application timings.** In general, there are two times when herbicides are applied, preemergence or postemergence. Preemergence, or “soil-applied herbicides,” control weeds at the seed germination stage, or as they are emerging from the soil (Figure 8.1). Products such as s-metolachlor (Dual Magnum®) and pendimethalin (Prowl®) must be applied before weeds germinate, otherwise they are ineffective. Soil-applied herbicides have residual activity and in general, provide weed control for about four to six weeks after application. Major factors that influence residual activity include soil moisture, soil pH, temperature, microbial activity, chemical decomposition, adsorption to soil structures, and plant uptake. As residual activity lessens, weeds begin to emerge during the season. At this point a postemergence herbicide may be necessary to provide adequate control for the remainder of the season.

Postemergence, or “foliar herbicides,” control existing weeds (Figure 8.2). Factors that influence their effectiveness include weed size, drought, temperature, rainfall, herbicide rate, spray volume, spray additives (adjuvants), and others. Certain herbicides provide both foliar and residual control (e.g., Callisto®, Classic®, atrazine, Reflex®) and are typically applied postemergence to control existing weeds and provide control of germinating seedlings. Other herbicides provide only foliar control (e.g., Roundup®, Gramoxone®, Aim®). Combinations of preemergence and postemergence herbicides may be necessary to control various types of weeds in an area.

Soil-applied and foliar-applied herbicides can be further defined by certain factors that occur when they are sprayed. Below are some common terms used to describe these scenarios.
Preplant: applied to soil and/or existing vegetation before the crop is planted.
- Used in situations where herbicides are sprayed to control weeds present at the time of crop planting (typically for no-till). This timing is often referred to as burndown or knockdown applications
- Nonselective herbicide can be included to terminate cover crops
- Residual herbicides are often included to control weeds emerging after application
- Used in situations where residual herbicides need to be applied prior to planting to reduce the risk of crop injury
- Early preplant often refers to applications made 2 to 4 weeks before planting

Preplant incorporated (PPI): applied to soil and mechanically incorporated into the top two to three inches of soil before the crop is planted.
- Used with certain herbicides that are only effective when mechanically incorporated
- This technique is not conducive to no-till situations

Preemergence (PRE): usually applied after the crop is planted but before the crop and weeds emerge.
- Rainfall or irrigation are typically required to move the herbicides into the soil (referred to as “activation”)
- Application should be delayed until after crop planting to prevent herbicide-treated soil from being disrupted and untreated soil exposed by the planter, row cleaners, or other operations

Postemergence (POST): applied after crop and weeds have emerged.
- Most postemergence herbicides need to be applied before the weeds are three inches tall and not intercepted by crop canopy to be most effective
- Post applications can be further distinguished into other stages and timeframes:
  ○ Early POST: weeds – ≤3 inches; corn – ≤6 inches; soybeans – one
unifoliate to trifoliate stage
- Mid POST: weeds – 2 to 6 inches; corn – ≤12 inches; soybeans – one to three trifoliates
- Late POST: weeds – <8 inches tall or as part of a split-application; corn – 12 to 20 inches; soybeans - >3 trifoliates but before flowering stage
- An adjuvant (i.e. nonionic surfactant, crop oil concentrate) is typically included to improve herbicide activity

**Application methods.** Herbicides can be applied differently depending on the situation. The following terms refer to the ways herbicides can be sprayed.

**Broadcast:** applied over the entire field typically with a boom sprayer (Figures 8.3 and 8.4).
- Refers to all application timings mentioned above

**Band:** applied as a narrow strip (ten to 12 inches) over the crop row (Figures 8.3 and 8.4).
- Typically refers to a preemergence herbicide applied after planting with spray nozzles attached to the planter
- Unlike a broadcast application, this allows for the herbicide to be applied only on a fraction of the field (i.e., width of spray pattern)
- Ensures herbicide-treated soil is not disturbed by planting operation (as often occurs with row cleaners)
- In areas not treated with an herbicide, cultivation, plastic mulch, or
other means of weed control is utilized

Directed: applied between the rows of crop plants with little or no herbicide applied to the crop foliage.
- Nozzles are placed below the top of the crop canopy with drop-tubes that extend from sprayer boom
- Crop safety and/or coverage of weeds can be improved below the crop canopy

Spot treatment: applied only to small or limited weed-infested areas within a field.
- Often used in areas prone to high weed pressure, such as pastures, roadsides, or field edges.

Weed Control Spectrum and Selectivity

Herbicide activity can be either selective or nonselective. Selective herbicides control certain weed species but do little or no damage to others including desirable plants or crops. However, not all crops are tolerant to all herbicides; similarly, not all weeds are controlled by all herbicides. Certain herbicides only control broadleaf plants, while others only control grasses. Many herbicides have activity on various broadleaf, grassy, and sedge weed species. Each herbicide has its strengths and weaknesses and for this reason, many of them are used in combinations to help complement their deficiencies.

Nonselective herbicides kill or injure almost all plants, including crops. Herbicide manufactures spend millions of dollars to test and develop many different chemicals in hopes of finding those that control a wide spectrum of weeds but are safe on a number of crops. Herbicide selectivity provides great value to the user in the fact that weeds can be discriminately and effectively controlled pre and/or post without injuring the crop.

Selectivity is accomplished primarily by two methods: selectivity by placement and true selectivity. Selectivity by placement avoids or minimizes contact between the herbicide and the desired crop. An example is wiping or directing an herbicide, such as glyphosate, on a weed without exposing the crop. Another way to direct an herbicide is the use of specialized shields or drop nozzles to focus the spray onto weeds without affecting crops. Applying an herbicide that does not readily leach beyond the soil surface to control of shallow-rooted weeds also is selectivity by placement – the herbicide does not leach into the root zone of a deeply rooted crop such as fruit trees or established alfalfa.

True selectivity is crop tolerance to certain herbicides as a result of some morphological, physiological, or biochemical process in the plant. The herbicide can be applied to the crop foliage or to the soil in which the crop is growing without danger of injury yet weeds that are sensitive to that herbicide will be controlled. In essence, the crop detoxifies the herbicide and is not injured. Although true tolerance may be better
than selectivity by placement, since it is essentially unaffected by the herbicide, it is not perfect. Sometimes true selectivity may not adequately prevent some crop injury under extreme growing conditions that make the crop more sensitive or stressed.

**Herbicide Movement in the Weed: Contact or Translocated**

Contact herbicides kill or injure only the part of the plant with which the spray droplets come into contact, so adequate spray coverage is very important (Figure 8.5). Annual weeds may be controlled, but regrowth of perennial weeds from belowground parts usually occurs following application of a contact herbicide (Table 8.2). Translocated (or systemic) herbicides are absorbed by the leaves or roots of the plants and move within the plant through the xylem or phloem tissue (Figure 8.5). Translocated herbicides are needed to kill underground parts of perennial weeds.
Table 8.2. Effect of herbicide type on weeds with different life cycles. (Source: Ross and Lembi. 1985. Applied Weed Science. Page 215.) G= good; F= fair; P= poor

<table>
<thead>
<tr>
<th>Herbicide type</th>
<th>Annual</th>
<th>Broadleaves</th>
<th>Biennial</th>
<th>Simple perennial</th>
<th>Creeping Perennials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grasses</td>
<td>Biennial</td>
<td>Biennial</td>
<td>Creeping Perennials</td>
<td>Seedling</td>
</tr>
<tr>
<td>Contact</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>G</td>
</tr>
<tr>
<td>Limited translocated</td>
<td>F to G</td>
<td>G</td>
<td>P to G</td>
<td>P to G</td>
<td>G</td>
</tr>
<tr>
<td>Well-translocated</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>Residual soil-applied</td>
<td>G</td>
<td>G</td>
<td>P - G</td>
<td>P - G</td>
<td>G</td>
</tr>
<tr>
<td>Long residual soil-applied</td>
<td>G</td>
<td>G</td>
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<td>G</td>
<td>G</td>
</tr>
</tbody>
</table>

Some Considerations When Using Herbicides

There are many kinds of herbicides from which to choose. Many factors determine when, where, and how a particular herbicide can be used most effectively. Understanding some of these factors enables you to use herbicides to their maximum advantage. Below are some fundamental issues about herbicides and their use. (For additional and specific information on herbicide use in field crops refer to the Mid-Atlantic Field Crop Weed Management Guide.)

As previously mentioned, the perfect herbicide does not exist. No single herbicide is capable of controlling all weeds that can develop in a crop or planting. Since every herbicide has advantages and disadvantages, selecting the correct herbicide or herbicide combination is crucial. Before choosing or applying an herbicide, the following should be considered:

- **Is it registered for use on the crop or area to be treated?** If so, read and follow label directions for use and rate of application. Recommended rates for soil-applied herbicides may vary according to soil texture and the amount of organic matter in the soil. Labels typically provide a range of rates to accommodate the effect that different soil types have on herbicide activity. Application rates for postemergence treatments vary with weed size and climate. Weeds growing under dry conditions or during prolonged cool weather will not actively translocate a systemic herbicide. A higher herbicide rate may be needed for dry conditions as compared to a standard rate when weeds are actively growing under ideal conditions.

- **Will the herbicide control the most troublesome weeds and does it include methods for managing herbicide resistance?** Many weed control measures fail
because the chosen herbicide will not control weeds that are present (see Chapter 7: Weed Resistance to Herbicides).

• **Can the herbicide be used effectively at the current stage of crop or weed growth?** Very few herbicides can be applied at any stage during the growth cycle of a plant. Pendimethalin (Prowl®) and s-metolachlor (Dual Magnum®) are good examples of how growth stage affects herbicide performance. They are excellent herbicides for annual grasses when applied before weed emergence. However, they are useless if applied after the weeds have emerged. Postemergence herbicides tend to be most effective when applied to small weeds (i.e., less than four inches tall). Aside from weed size, the size of the crop can also affect postemergence herbicide applications. If crops are too large (as defined on the herbicide label), the herbicides may cause reduced crop vigor, interfere with reproductive processes, and ultimately reduce yield. Also, a large crop’s leaves can intercept the herbicide before it reaches its intended weed target and result in poor weed control.

• **Can the soil-applied herbicide be used effectively and safely under the current conditions?** Soil-applied herbicides must be absorbed by roots and shoots of weed seedlings. Rainfall is usually adequate to incorporate soil-applied herbicides, but without rainfall, weed control may be poor. The effectiveness of soil-applied herbicides also can be reduced if the product is not applied at a high enough rate or is intercepted by crop residue, existing vegetation, a prior application of livestock manure, or other barrier. Reduced-tillage cropping systems may require higher application rates of soil-applied herbicides than conventional tillage systems, depending on the amount of crop residue. Herbicides also can be lost to runoff, leaching, or volatilization/vaporization.

• **How does the herbicide or herbicide combination interact with other pesticides, fertilizers, or other inputs being used on the crop?** Certain combinations may cause undesirable results if mixed together in the same spray solution resulting in injury or death to desirable plants or disabling equipment. For example, some organophosphate (OP) insecticides interact negatively in the crop with ALS-inhibitor (Group 2) herbicides. Water mixes well with 2,4-D amine in the spray tank but if liquid nitrogen solution is used in place of water (e.g., in a “weed and feed” application), a gelatinous precipitate results and cannot be sprayed; furthermore, the sprayer is rendered useless until a very difficult clean out procedure is accomplished.

• **How does herbicide utility interact with other integrated weed management (IWM) strategies?** The use of herbicides must complement other weed control tactics to be effective. For example, herbicides can be an important tool to terminate cover crops prior to planting the cash crop. If the herbicide is also intended to control weeds near ground level, the cover crop may intercept most
of the herbicide, resulting in poor weed control. Another IWM approach, for example, combines mechanical and chemical tactics to control weeds. A field could be tilled in order to stimulate weed seed germination. Once the green growth of the weed flush appears, an herbicide can be applied to control the new growth.

- **Does the crop require the use of a “safener”?** Herbicide safeners, also called antidotes or protectants, are chemicals that help prevent injury to crops without reducing weed control. Some safeners are included in the herbicide formulation while others need to be applied to the seed prior to planting. Products such as Dual II Magnum® and Resolve Q® include safeners.

- **Is the herbicide being applied to a “conventional” (i.e., non-GMO) or genetically modified (GMO) crop?** Since genetically modified crops look similar to conventional crops, misapplication can occur and the crop can be unintentionally injured or killed. Make sure to record the type of crop planted in each field.

- **Will herbicide residues carryover to the next crop or cover crop and result in injury?** Herbicide carryover is a problem with chemicals that persist in sufficient quantity to injure successive plantings (often referred to as “rotational crops”). Herbicides prone to carryover include triazines (atrazine and simazine), dinitroanilines (Treflan®, Curbit®, Prowl®), ALS inhibitors (Classic®, FirstRate®, Pursuit®), and pigment inhibitors (Command®, Balance®, Callisto®). These herbicides can provide season-long control of certain weeds. However, if an excessive rate is applied, soil pH is above 7.0, or weather during the growing season is cool and dry, natural breakdown of the chemicals may not occur, leading to carryover. Read labels carefully for warnings about carryover and crop rotation concerns.

- **What factors are necessary for a successful application?** What is the appropriate method of application (i.e., broadcast, band, directed, spot)? Is it convenient to use in such a form as a ready-to-use (RTU) product, or does it require special equipment? Should it be mixed with water before application? Are there other characteristics, such as compatibility with other pesticides when tank-mixing or staining, that make it difficult to use?

- **Does the herbicide label recommend that a surfactant, crop oil, or other additive (adjuvant) be used?** Many postemergence herbicides require the use of an adjuvant in the mixture. These are special products that are added to the spray mixture to improve herbicide activity or optimize application characteristics.

- **Can this product be used safely?** What is required during and after use to safely handle, mix, and apply the product? Is it a restricted-use pesticide (RUP)? When using an RUP, the handler and applicator must have a special license (obtained
through the state’s Department of Agriculture) to work with such products.

- **Can the herbicide injure non-target plants in adjacent areas?** Exercise caution to avoid drift, runoff, leaching to groundwater, and cross-contamination of other materials. Be especially aware of herbicide residues in sprayers when spraying a different crop.

### Herbicide Resistance

A number of weed species that were once susceptible to and easily managed by certain herbicides have developed resistance to those herbicides and are no longer controlled by them. Certain precautions, such as tank-mixing multiple and effective herbicides, crop rotations, and a combination of weed management techniques, must be taken to prevent resistance. However, some cases of suspected herbicide resistance may actually be due to improper herbicide application (e.g., weeds too large, dry weather, improper herbicide used, etc.) and not actual resistance to an herbicide (see Chapter 7: Weed Resistance to Herbicides).

Farmers, consultants, and herbicide applicators should know which herbicides are best suited to combat specific resistant weeds. The Weed Science Society of America (WSSA) developed a grouping system to help with this process. Herbicides that are classified as the same WSSA group number use the same mode of action to control weeds. WSSA group numbers can be found on many herbicide product labels. They can be used as a tool to choose herbicides with different modes of action so mixtures or rotations of active ingredients can be planned to better manage weeds and reduce the potential for resistant species.

### Drift

Drift is the movement of any pesticide through the air to areas not intended for treatment. During application, physical drift occurs as spray droplets or dust particles are carried by air movement from the application area to other places. Vapor drift takes place after application as herbicides evaporate (volatilize) and the vapors (gases) are carried on wind currents and deposited on soils or plants in untreated areas. In general, physical drift of spray droplets occurs before the droplets reach their intended target whereas, vapor drift occurs after the herbicide reaches its target and changes to gas and then moves.

Drift may injure sensitive crops, ornamentals, gardens, livestock, wildlife, or people and may contaminate streams, lakes, or buildings. It may contaminate crops and cause illegal or excess residues. Excessive drift may mean poor performance in the target spray area because the actual amount of herbicide working in the area is lower than expected.

Drift control should be considered with each pesticide application. Severe drift problems can be prevented by using:
• Sprayer nozzles designed for drift reduction
• Low volatile or nonvolatile formulations
• Low spray-delivery pressures (15–40 psi) and nozzles with a larger orifice (hole)
• Drift-inhibiting adjuvants in the spray mixture when spraying under less-than-ideal conditions
• Nozzles that allow for lowered boom height

Drift problems can also be prevented through the following practices:
• Avoiding application of volatile chemicals during hot weather (>80°F)
• Spraying when wind speeds are low (<10 mph) or when the wind is blowing away from areas that should not be contaminated
• Spraying during the early morning or evening hours when there is usually less wind
• Avoiding application when conditions are favorable for temperature inversions (very still air, usually early evening into early morning hours)
• Leaving field borders unsprayed if they are near sensitive crops

Herbicides in Organic Cropping Systems

Using synthetic herbicides is generally not allowed in organic crop production systems. The USDA National Organic Program (NOP) does allow certain nonsynthetic soap-based herbicides for use in farmstead maintenance (roadways, ditches, right of ways, building perimeters) and ornamental crops. In addition, several products that contain natural or nonsynthetic ingredients (e.g., vinegar, clove oil, cinnamon oil, citrus oil, lemon grass oil, etc.) are classified as approved by the Organic Materials Review Institute (OMRI). The OMRI listing does not imply product approval by any federal or state government agency. It is the user’s responsibility to determine the compliance of a particular product. Allowable materials can change frequently. Because the classification of a material as allowable for organic production is subject to change, it is strongly recommended that organic farmers confer with their certifiers before purchasing or applying any pest management substance to avoid loss of organic certification. Additional information about “organic herbicides” or “bio-herbicides” and their utility can be found in the Penn State Organic Crop Production Guide.
Key Points

- Herbicides can be defined as crop-protecting chemicals used to kill weedy plants or interrupt normal plant growth.
- Herbicides provide a convenient, economical, and effective way to help manage weeds.
- In most cases, they can be the backbone of many weed management programs. However, they should not be used alone but integrated with effective nonchemical tactics.
- The perfect herbicide does not exist. No single herbicide is capable of controlling all weeds that can develop in a crop or planting. Since every herbicide has advantages and disadvantages, selecting the correct herbicide(s) is crucial.
- Most herbicides are typically applied to the soil (preemergence) before weeds germinate or after weeds are growing (postemergence).
- Herbicides can be classified several ways, including by weed control spectrum, labeled crop usage, chemical families, mode of action, application timing/method, and others. In most cases, herbicides will be grouped according to mode and site (or mechanism) of action mostly to assist with herbicide resistance management.
- Herbicides can be categorized in different ways and by certain characteristics, including: a) mode and site of action; b) application timings and methods; c) weed control spectrum and selectivity; and d) herbicide movement in the weed.

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Mid-Atlantic Field Crop Weed Management Guide (https://extension.psu.edu/mid-atlantic-field-crop-weed-management-guide)

TeeJet Technologies, a subsidiary of Spraying Systems Co. (http://www.teejet.com)


Organic Materials Review Institute (https://www.omri.org)
Chapter 9: Biological Weed Control

William Curran, Meredith Ward, and Matthew Ryan

Summary

Biological control (biocontrol) tools for weeds include insects, mites, nematodes, pathogens, and grazing animals. Grazing animals and insects can directly impact weeds and reduce their growth and competitiveness. Other biocontrol organisms will feed on weed seeds and reduce seed return to the soil seedbank.

Introduction

Biological weed control is the deliberate use of the weeds natural enemies to reduce the density to a tolerable level. This method is not intended to eradicate the target weed but exerts enough pressure on the weedy plant to reduce its dominance to a more acceptable level. Biological control can be cost effective, environmentally safe, self-perpetuating, and well suited to an integrated weed management program. However, it is a long-term undertaking, the effects are neither immediate nor always adequate, and it only works certain weeds.

There are four methods of biological weed control:
1) Classical - using a non-native control agent (usually an insect) to reduce an invasive weed;
2) Inundative - production of an organism that is released at high numbers to control native or invasive weeds;
3) Conservation - manipulating a cropping system to increase the populations of natural weed suppressing organisms; and
4) Grazing - using large herbivores such as cattle and sheep to reduce weed populations.

Classic and Inundative Biocontrol

In the Northeast, classical and inundative biocontrol tactics are being used on several invasive weeds such as bull and musk thistle, Canada thistle, purple loosestrife, mile-a-minute, and garlic mustard. In addition to the several promising insect biocontrol tools being examined, several rust fungi and bacteria are being evaluated for managing several weeds, including the knapweeds and the thistles. Most of the potential for classical and inundative tactics are focused in perennial systems.
with low annual disturbance. Frequent disturbance such as tillage, mowing, or even natural phenomena such as fires or floods will greatly affect the survival of biocontrol organisms. Over the long term, in rangeland, pasture systems, and natural areas, these biological weed control tactics may have a major impact on managing problem weeds in the future.

In agronomic crops where disturbance is common (tillage, mowing, etc.), classical and inundative biocontrol tactics are not currently available. However, managing grazing animals and using conservation tactics have the greatest potential to reduce weed populations. Both of these tactics provide broad spectrum weed control. In this chapter we will briefly discuss these biocontrol tactics.

**Conservation Biocontrol**

Conservation biocontrol relies on understanding the biology and habitat suitability of the organisms that feed on weeds or weed seeds. This knowledge is then used to adjust management practices so that these organisms that include mostly insects (invertebrates) and rodents are promoted or encouraged. For example, establishing a winter cover crop using no-till is a conservation biocontrol practice because it protects invertebrates in the cropping system, such as ground beetles, which consume weed seeds on the soil surface. Establishing windrows that provide habitat for rodents such as field mice is another conservation biocontrol practice. Both of these groups of organisms readily feed on weed seeds potentially reducing the number of weeds that emerge the next year. Reducing soil disturbance and providing ground cover or refuge from the predators of insects and rodents is one of the key ways these naturally occurring biocontrol organisms are conserved.

Conservation biocontrol may improve our ability to manage weeds using less herbicide. This practice reduces weeds by enhancing existing populations of invertebrates and rodents that are already present to help keep weed populations in check. This is not an inundative or augmented tactic where organisms are released, but rather an approach to create more favorable habitats that are attractive to the insects and rodents already present. These natural biocontrol organisms are then active when weeds are vulnerable. Organisms that feed on weed seeds (weed seed predators), are active when weed seeds are maturing (predispersal) and after they are dispersed (postdispersal). Sole use of biological control will not be effective enough to completely suppress weeds and limit crop yield loss, but combining conservation biocontrol with other cultural, mechanical or chemical management tactics could have a greater positive impact than any single tactic alone.

Numerous organisms are weed seed predators. Some of the most common (and promising) are rodents, ants, crickets, and ground beetles. The amount of seeds consumed will vary depending on predator populations, weed seed availability, and field management. Reducing tillage, providing residue cover, and limiting insecticide
use are key field management requirements. In an Iowa study, seed predation rates from May to November ranged from 7 to 22% of available weed seeds consumed or removed per day depending on crop type (Figure 9.1) (Westerman et al. 2005). Higher predation rates were observed in small grains and alfalfa compared to corn and soybeans. The rate of seed predation typically increases as the crop canopy develops spring-planted corn and soybean crops provide little protection for seed predators early in the growing season compared to small grains or established alfalfa. In a Pennsylvania study (Ward et al. 2011), 38 to 61% of the giant foxtail seeds were removed (eaten) during two-week sampling periods in sweet corn with peak predation occurring in late July and early August when the corn canopy was well developed (Figure 9.2). In another Iowa study, predation of giant foxtail seeds in wheat increased by overseeding wheat with red clover in the spring (Davis and Liebman, 2003). Seed predators likely seek habitats that provide adequate cover for their protection and a plentiful food source.

![Figure 9.1. Seed predation rates in five cropping systems, with more predation in systems with less tillage. (Source: Westerman et al. 2005)](image-url)
Knowing the most important weed seed predators and the management tactics that promote their conservation is poorly understood. However, typical farming routines such tillage practices and crop rotation can often be slightly changed to incorporate management practices that increase populations of weed seed predators. For example, integrating a legume cover crop after small grains in a farming rotation may enhance predation by providing protection for seed predators. Creating refuge strips of perennial grasses around the boundary of crops and in waterways can create favorable habitat for ground beetles, fungi and nematodes. Increasing plant residue and decreasing tillage, especially in the fall, can cause certain seed predator populations to flourish.

**Potential beneficial seed predators.**

**Mice.** Mice are opportunistic feeders, consuming the easily available high-density food source. As a result, seeds are their primary food (Zhang et al. 1997). Mice can consume 90 - 100% of an area’s weed seeds in a 12-hour period. High seed removal rates are the result of rodents finding a high density food source, filling their mouths with as many seeds as possible, storing the seed and making repeated trips back to collect seeds until all the seeds are utilized (Abramsky, 1983).

Rodents locate seeds using their olfactory senses and can even find seeds buried under the soil surface (Table 9.1) (Abramsky, 1983). Rodents feed first on the larger
seeds of dicot weeds (Cardina et al. 1996) such as velvetleaf, giant ragweed, eastern black nightshade, jimsonweed and morning glory. They then shift to smaller seeds only after most of the bigger seeds have been utilized (Abramsky 1983). Mice are also one of the few weed seed predators that consistently eat hard shelled seeds (Brust and House 1988). Unfortunately, mice can be problematic in some cropping systems by feeding on crop seeds or disrupting irrigation equipment, plastic mulch, and other agricultural tools. Encouraging vertebrate predators like mice may be best suited to large scale annual row crop production where the risk of crop or equipment damage is minimal.

Table 9.1. Efficiency of removal of buried barley seed by rodents (Abramsky 1983).

<table>
<thead>
<tr>
<th>Depth (in)</th>
<th>Amount of seeds removed (g)</th>
<th>% removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>102</td>
<td>79</td>
</tr>
<tr>
<td>1.2</td>
<td>104</td>
<td>80</td>
</tr>
<tr>
<td>2.0</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>6.0</td>
<td>47</td>
<td>47</td>
</tr>
</tbody>
</table>

**Ants.** Most of the research examining ants as weed seed predators was conducted in Europe and Australia with little information from the United States. Ants are diurnal insects that spend the day actively foraging and feeding and they remain in their nests at night. Ants have been found to feed on weed species with small seeds (Brust and House 1988) such as common ragweed, redroot pigweed, and common lambsquarters. In pastures, these insects can remove up to 43% of small seeded weed seeds over a 20-day interval and 2 - 30% of annual ryegrass seeds within 24 hours (Jacob et al. 2006). Feeding preference studies have shown that the amount of each seed type removed by ants was strongly influenced by the amount and kinds of other seeds in the immediate area (Zhang et al. 1997). This suggests that certain weeds seeds will be more readily consumed than others. Ants also tend to colonize in agricultural fields in high numbers; however, their activity can be reduced by tillage and higher levels of crop residue or stubble (Jacob et al. 2006). This suggests that ants could be important seed predators in row crops after inter-row cultivation has ceased.

**Crickets.** When crickets gather in large numbers in new seedings of no-till alfalfa and clover, they are considered a pest. However, they can also be important weed seed predators. Crickets are nocturnal omnivores that consume dead and living insects, broadleaf plants, grasses, and seeds. They emerge in early August with peak activity in the middle of September and populations decrease in October (Carmona et al. 1999). Field observations and laboratory studies showed crickets consume common agricultural weed seeds such as velvetleaf, common lambsquarters, redroot pigweed
and waterhemp, large crabgrass, common ragweed, and giant foxtail. Cricket populations tend to peak in late summer about the same time that summer annual weeds produce and shed seeds. Crickets can remove more than 76% of weed seeds in 24 hours (Figure 9.3), and a single female northern field cricket can consume over 200 redroot pigweed seeds in a single day (Carmona et al. 1999).

Figure 9.3. Ground beetle (*Harpalus pensylvanicus*) activity (left) and giant foxtail seed rain (right) over time in 2006 in Pennsylvania. Activity density numbers represent how many beetles are active and captured over a 72-hour period. Although the presence of the beetle overlapped with giant foxtail seed rain, beetle activity was greater in August and early September, while foxtail seeds were not dispersed until later in the fall. (Source: Ward et al. 2014)

**Carabid beetles.** Ground beetles, otherwise known as carabid beetles, are common throughout the Mid-Atlantic region in agricultural landscapes (Photo 9.1). *Harpalus pensylvanicus*, a common carabid found in Pennsylvania and a known seed predator, emerges from hibernation in the spring, and is most active from July through September in the Mid-Atlantic region. Adults consume plant tissues, pollen, fungi, insects and seed, preferring smaller sized broadleaf and grass seeds (Best and
Ground beetles can be responsible for up to 90% of weed seed predation in some agroecosystems. A single ground beetle can consume up to 11 seeds daily, and seed removal can be as high as 120 to 130 seeds/square foot/day from an active population of ground beetles (Honek et al. 2003). Research at Penn State showed that ground beetles readily consume giant foxtail seeds but that the time when *H. pensylvanicus* is active and giant foxtail is shedding seed has some but only slight overlap (Ward et al. 2014). In 2006, *H. pensylvanicus* was most abundant in late August, while giant foxtail seed shed did not peak until mid-October (Figure 9.3). In contrast, yellow foxtail seeds mature and shed earlier than giant foxtail and may be better timed to the presence of this common ground beetle. This suggests that other predators may be more effective in removing giant foxtail seeds than *H. pensylvanicus*.

Unlike rodents, ground beetles do not survive intense disturbances, such as fall or spring plowing. Fortunately, many ground beetles are fairly mobile and they can abandon fields in autumn and overwinter in fence rows and other field edges and water ways. They do not necessarily prefer one crop over another but may prefer different crop types throughout the growing season. Decreasing or eliminating soil disturbance, especially in the late summer when beetles are feeding, mating, and laying eggs can increase ground beetle activity.

Although conservation biocontrol could be an important part of a weed management program, this tactic is not completely understood. Additional research is needed. Individual farmers can incorporate practices that encourage weed seed predation and monitor how this is affecting their weed control program. Integrating conservation biocontrol is only one tool that needs to be added to a suite of practices that complement each other to reduce the return of weed seeds annually to the seedbank.

**Grazing Animals**

Grazing management minimizes the spread of certain weeds and controls large infestations. However, in most cases grazing does not eradicate a mature infestation of weeds. For grazing animals to be useful for weed control, they must be fenced into or out of an area in order to adjust grazing pressure. Increasing grazing pressure (animal numbers and duration) at key times during the growing season prevents livestock from grazing selectively (eating some plants and not others) forcing them to consume more undesirable species. The key to this method of weed control is to concentrate stock on weed infestations at key stages of growth and keep them off pasture or weeds at other times (Popay and Field, 1996). For example, intense grazing of the winter annual downy brome or the herbaceous perennial Canada thistle in the spring and early summer can reduce the growth of the weeds and competition to desirable forages. Most livestock avoid these same weeds later in the summer after they are mature and less palatable and they have already flowered and produced seed.
When grazing is restricted to only one class of livestock, it generally leads to particular weed problems because some plants are less desirable to some classes of stock. Cattle, sheep, and goats are the most common animals used for grazing pasture. Horses also graze weeds. Pigs sometimes graze grass, but their weed control activities are associated more with their rooting behavior. Domestic birds also eat grass and have been known to graze weeds selectively. Only the use of cattle, sheep, and goats is discussed in this chapter. Combining ruminant grazing with other weed management tools such as herbicides can offer a more cost-effective integrated approach.

**Cattle.** Although cattle prefer grasses and tend to avoid forbs and shrubs, they have large rumens and are able to digest fibrous material (Frost and Launchbaugh 2003) including mature weeds. In Boulder, Colorado, cattle have been taught to graze weeds as part of an integrated weed management program, reducing herbicide use and costs (Voth, 2008). Cattle can provide effective control partly because of their grazing patterns and partly because their hooves damage young, tender, emerging shoots. Grazing pastures in early summer when most biennial and perennial weeds such as dandelion, broadleaf plantain, or even biennial thistles are most palatable and sensitive to livestock traffic can reduce infestations. However, constant grazing by cattle reduces grass forage and promotes forbs and shrubs, some of which may be weeds. Grazing on their favorite species and overgrazing creates more problems, like bare patches in pastures, which allow the invasion of new weed seedlings or the proliferation of perennials. Previous research showed that grazing high stock numbers infrequently reduced Canada thistle shoot density and biomass as well as flowering and resulted in greater weed suppression than grazing fewer animals more frequently (De Bruijn and Bork 2006).

**Sheep.** Sheep are considered excellent at controlling herbaceous weeds as they tolerate high fiber-containing plants including forbs. In general, they prefer broadleaf plants (forbs) over grasses and shrubs. Grazing by sheep is a major method of biological weed control on dryland farms in Victoria, Australia where they are used during fallow periods to reduce weed seed production before annual cropping. In Saskatchewan, Canada continuous summer-long sheep grazing reduced the number of leafy spurge from about 320 seeds per square foot to 1.5 seeds per square foot after eight years (Bowes and Thomas 1978). In this experiment, sheep grazing had no effect on leaf spurge stem density for the first three years, after which the density declined dramatically. Sheep have been used to effectively control leafy spurge along several major rivers in Montana in a state-sponsored weed control program (Gwin et al. 2001). Sheep also have been successful in controlling Canada thistle. The young, soft, aerial thistle shoots must be intensively grazed in spring which is not always possible because of lush pasture growth producing ample forage during that time. However, combining an herbicide application or mowing and haying with grazing can provide a wider window of time for effective control.
Goats. Goats can control a large number of spiny and prickly weed species totally untouched by sheep and cattle. Goats have narrow and strong mouths well designed for stripping leaves and woody stems. They are classified as browsers and are generally able to tolerate potentially toxic compounds better than cattle or sheep (Frost and Launchbaugh 2003). In a North Carolina study, 12 goats per acre alone or seven goats per acre mixed with cattle mostly eliminated multiflora rose and some other weeds from an abandoned orchard after four grazing seasons (Luginbuhl et al. 1998). In the same experiment, desirable forage species increased in number over time. Goats also have been used successfully for general brush control on abandoned farmland in Vermont (Wood, 1987). While goats eagerly consume flowering thistle plants, they are not attracted to the vegetative rosette.

Combining small ruminant grazing with other weed management tools has considerable promise for controlling certain weed species. For example, grazing Canada thistle with sheep and goats during the spring and fall, followed by a fall application of an appropriate herbicide, can have a greater impact on the weed than either tactic used alone. In addition, adding sheep or goats to a cattle enterprise for control of weeds or to help clear land of undesirable vegetation can be profitable. In a West Virginia study, the cost of using goats to help control brush was compared with mechanical and chemical control tactics. The three-year variable costs for brush clearing with goats was estimated at $13.50 per acre versus $54 for mechanical cutting and $240 per acre for herbicides (Magadlela et al. 1995).
**Key Points**

- Biological control tools for weeds include insects, mites, nematodes, pathogens, and grazing animals.
- Biological control can be cost effective, environmentally safe, self-perpetuating, and well suited to an integrated weed management program.
- Biological control is a long-term undertaking; it is not immediate or always adequate, only certain weeds are potential candidates, and the rate of failure can be high.
- Combine mowing or an herbicide application with grazing to provide a wider window for control.
- Biological weed control may have a major impact on managing problem weeds in pasture systems in the future.
- Seed predation can be responsible for up to 90% of seed loss in agroecosystems.
- Some of the most promising seed predators are rodents, ants, crickets and ground beetles.
- Reduce tillage events and use conservation tillage and no-till practices can also increase predation. Weed seed predation occurs mostly on the soil surface.
- Cover crops decrease tillage and herbicide use and create better habitats for seed predators.
- Promote and maintain diverse fencerows, filter strips, and refuge habitats that allow overwintering sites and protection for ground beetles, rodents, crickets and other seed predators.

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Chapter 10: Cultural Control

Charlie Cahoon

Summary

Crop rotation, variety selection, soil fertility, planting date, seeding rate, row spacing, leaf architecture, and disease and insect management are considered cultural weed control (in other words, good agronomic practices). These methods are used to produce a healthy crop that can efficiently compete with weeds.

Introduction

Crops and weeds continually compete for valuable resources, including light, nutrients, water, and space. Cultural weed control encompasses any tactic that creates a competitive advantage for a crop. A more competitive and healthier crop better suppresses weed growth. Ultimately, this comes down a “survival of the fittest” contest between crops and weeds.

Many cultural techniques for weed management have been employed since the beginning of cultivated agriculture, but their contributions to weed control are often overlooked. Examples of cultural weed control include selecting varieties adapted to the area; manipulating seeding rates, row spacing, and planting dates; maintaining soil fertility; scouting for and controlling insects and diseases; and rotating crops. To boost crop yield, quality, and economic return, farmers frequently employ all of these techniques which include their weed control benefits. Many of these tactics quickly establish a crop canopy and maximize the amount of sunlight captured by the crop. Because the dense crop canopy captures the sunlight, the amount of light available to weeds decreases. The following sections will discuss specific cultural weed management tactics more in depth.

Crop Rotation for Weed Management

Crop rotation is often touted for increasing crop yield by improving soil fertility and suppressing insect and disease pests. Strategic crop rotation also increases the crop’s ability to suppress weed growth.

Planting crops with varying growth habits, growing seasons, and characteristics, disrupts weed life cycles. Different crops have varying planting dates and different times that weed management is imposed. Knowing this information, farmers can
manipulate their cropping system to prevent one weed species from becoming dominant. For example, Italian ryegrass is a troublesome winter annual weed infesting winter small grains. To avoid Italian ryegrass, farmers can plant summer annual crops and work to control Italian ryegrass during the fallow period. Ensuring Italian ryegrass did not reproduce for a few season, the farmer can return to growing winter small grains with less of Italian ryegrass problem. In addition, using a more competitive crop to suppress certain weeds can be helpful prior to planting a less competitive crop. A more competitive crop will rapidly establish its canopy or maintain its canopy longer compared to a less competitive crop which is slow to canopy or may have a short-lived canopy. For example, in a Maryland study, researchers observed that corn planted after hay had fewer smooth pigweed and common lambsquarters than corn planted after Italian ryegrass did not reproduce for a few season, the farmer can return to growing winter small grains with less of Italian ryegrass problem. In addition, using a more competitive crop to suppress certain weeds can be helpful prior to planting a less competitive crop. A more competitive crop will rapidly establish its canopy or maintain its canopy longer compared to a less competitive crop which is slow to canopy or may have a short-lived canopy. For example, in a Maryland study, researchers observed that corn planted after hay had fewer smooth pigweed and common lambsquarters than corn planted after Italian ryegrass. Pigweed and lambsquarters, which are more competitive with soybeans than a densely planted hay crop, produced more seed in soybeans than hay. In addition, the hay crop was periodically mowed, which reduced seed production of smooth pigweed and common lambsquarters. This resulted in a greater weed problem in corn planted after soybeans compared to corn planted after hay. The opposite was true for grass species; grasses are difficult to control in hay. Annual grasses were denser in corn planted after hay than corn planted after soybean.

Crop rotation also is important when planning herbicide programs. Herbicide use varies by crop and rotating crops allows farmers to use alternative herbicide modes of action (see Chapter 8: Chemical Control). Rotating herbicide modes or sites of action is essential in avoiding herbicide resistance. Additionally, the ease of controlling a certain weed in a rotational crop often depends upon herbicides available for use in that crop. For example, in the Mid-Atlantic region, common lambsquarters was found to be more easily controlled in a corn-soybean and corn-tomato-soybean rotation than in a continuous soybean system (Manley et al. 2001) (Figure 10.1). In this study, each crop received a different combination of herbicides. Soybean plots received a mixture of fomesafen (Reflex®) and fluazifop plus fenoxaprop (Fusion®); corn plots received a mixture of atrazine and butylate (Sutan +); and tomato plots received a mixture of metribuzin and trifluralin (Treflan®). Because the mixture of fomesafen and fluazifop plus fenoxaprop did not effectively control common lambsquarters, the weed was able to reproduce in years dedicated to growing soybeans. In contrast, herbicides used for corn and tomato plots controlled common lambsquarters well, so common lambsquarters density was reduced when these crops were incorporated into the rotation. In the same study, jimsonweed proved more difficult to control in the corn-tomato-soybean rotation compared to rotations that did not include tomato. The mixture of metribuzin and trifluralin applied to tomato plots did not effectively control jimsonweed. Left uncontrolled in tomato, jimsonweed was able to reproduce and became more challenging to control in subsequent corn and soybean.
Crop Variety Selection

Crop management decisions influence weed control. Selecting vigorous crop varieties will limit competition from weeds and reduce weed seed production. Farmers should plant crop cultivars most adapted to local planting date and growing conditions. Varieties that quickly form a dense canopy are often more competitive than slower growing cultivars. In addition, full-season varieties may be more competitive compared to earlier-maturing lines because their canopy stays fuller longer, shading out weeds. For example, following a postemergence spray, North Carolina researchers reported more late-season weeds in an early-maturity soybean cultivar than a more full-season variety (Yelverton and Coble 1991). Early leaf shed of crops allows more light to penetrate the canopy thus encouraging weed development late in the season. Canopies of later-maturing varieties impeded light for a longer duration than early-maturing varieties. Likewise, another North Carolina study reported three winter wheat varieties differed in their ability to suppress Italian ryegrass (Worthington et al. 2013). In this study, taller cultivars were more competitive with Italian ryegrass by decreasing light penetration through the canopy compared to shorter cultivars.

Farmers also should consider disease and insect tolerance in variety selection. Disease or insect tolerant varieties are healthier in the presence of disease and insects compared to cultivars susceptible to these stressors. In the presence of disease or
insects, tolerant varieties out-compete weeds, but varieties crippled by disease or insects succumb to weed pressure.

**Soil Fertility**

Farmers often apply soil amendments, including fertilizers and lime, to achieve higher crop yields. However, these amendments also can jumpstart crop growth which establishes a competitive advantage over weeds. For example, wheat is more responsive to nitrogen than the weed Persian darnel (Blackshaw and Brandt 2008). Persian darnel growth is favored when the soil is low in nitrogen. Therefore, wheat is more competitive with Persian darnel when sufficient nitrogen is supplied than if nitrogen is limited. A similar phenomenon is seen with phosphorus. Downy brome, henbit, and wild oat are more responsive to phosphorus than wheat; therefore wheat is more competitive with these species under low phosphorus conditions (Blackshaw and Brandt 2004). In addition, soybeans are capable of creating their own nitrogen with nitrogen-fixing bacteria. Limiting external nitrogen while producing soybeans starves weeds of an essential nutrient without penalty to the crop. Fertilizer applications should focus on feeding the crop. Supplying only what the crop needs limits surplus nutrients that otherwise would be used to fuel weed growth. This prevents the waste of money spent on excess fertilizer. Farmers should also consider nutrient placement. A nutrient’s close proximity to a crop allows roots to readily access nutrients that weeds may have to work harder to reach.

Soil pH also can favor one species over another. Most plants grow best at slightly acidic to near neutral soil pH. However, some plants require more acidic or alkaline conditions. Buchanan et al. (1975) reported large crabgrass could tolerate soil pH as low as 4.8, whereas redroot pigweed was less vigorous at pH 5.3 or below. This means under acidic conditions, when most crops suffer, some weeds gain the upper hand.

Maintaining a competitive crop means paying close attention to soil fertility and supplying soil amendments, such as nitrogen, phosphorus, potassium, other nutrients, or lime, in a timely manner. Consider the 4 Rs of nutrient stewardship: right source, right rate, right time, and right place when fertilizing crops to ensure the crop is healthy and can compete with weeds to the best of its ability (TFI 2017). Right source means choosing a fertilizer that best matches your crop’s nutrient needs. The right rate is achieved by matching fertilizer rates with crop nutrient demand. Coordinating fertilizer applications when the crop needs nutrients corresponds to the right time. And right place means placing nutrients where the crop can best utilize them.

**Planting Date**

Planting date can be manipulated to create a more competitive crop or cover crop. If planned strategically, planting date can give crops a competitive edge. Farmers should choose planting dates that encourage a crop’s rapid emergence (warm seedbed,
warm air temperatures, and adequate soil moisture), early-season growth, and formation of a dense canopy. The goal is to form a dense crop canopy that efficiently gathers sunlight and shades out weeds as quickly as possible.

Planting crops when conditions are not favorable for germination and development of certain weeds is also important. A Maryland experiment studied the effect of delaying corn planting on plant weight of several weed species (Teasdale and Mirsky 2015). In this study, common ragweed, giant foxtail, and corn weight changed little over planting dates ranging from May 7 to June 30. However, smooth pigweed weight increased 10.5 grams from the earliest to latest planting date. This means that early planted corn was more competitive with smooth pigweed than the later planted crop.

While initial germination of weeds varies each year, the emergence sequence of weeds in a population is fairly consistent (see Chapter 3: Weed Emergence, Seedbank Dynamics, and Weed Communities for more information). For example, common ragweed is one of the first summer annual broadleaf weeds to emerge during the spring. Pigweed species normally germinate later than common ragweed. Knowing when weeds emerge can be useful in determining planting dates that give crops a competitive advantage over weeds. Corn is normally planted two to four weeks earlier than soybeans. When planting corn, early-emerging weed species, such as common ragweed or common lambsquarters, pose more of a threat than late-emerging weeds like pigweed species. Early-emerging may germinate before or shortly after corn emerge, giving them the opportunity to use light, moisture, nutrients, and space that would otherwise be available to the corn. However, late-emerging species may not germinate until after a dense corn leaf canopy has been established, capable of suppressing weed growth.

Germination of early-emerging weeds would be near completion when soybeans are planted. Therefore, early-emerged weeds can be removed by mechanical or chemical methods prior to planting soybeans with less chance of more emerging after planting. Late-emerging weeds may emerge after soybean planting and would be more difficult to control in soybeans than in corn. With this knowledge, farmers can adjust planting dates such that crop and weed emergence do not occur simultaneously.

Planting date also plays an important role in cover crop biomass (total plant weight) accumulation and subsequent weed control by the cover crop. Nord and others (2012) reported cereal rye sown in September accumulated more biomass and was a better suppressor of weeds than cereal rye sown in October. Likewise, hairy vetch (Teasdale et al. 2004a) and mixtures of rye and hairy vetch (Mirsky et al. 2011) biomass declines as planting is delayed and subsequent weed control is reduced. Because cover crops planted early in the fall accumulate more biomass, they may better suppress weeds the following spring.
Seeding Rate, Row Spacing, and Leaf Architecture

Achieving rapid crop canopy closure is critical to establishing a competitive advantage over weeds and is key to cultural weed management. As a crop canopy closes, light interception by weeds is interrupted, suppressing weed growth and development (Yelverton and Coble 1991). Adjusting seeding rate and row spacing are the simplest ways to enhance canopy closure. Crops planted at higher seeding rates can reach canopy closure much quicker than crops planted at lower seeding rates. Many studies from the Mid-Atlantic region have demonstrated the weed control benefits of increasing seeding rates and utilizing narrow row spacing. In an organic soybean production system, redroot pigweed density decreased from approximately 32,000 to 12,000 plants per acre as soybean seeding rate increased from 75,000 to 225,000 seed per acre (Place et al. 2009). Similarly, increasing spring wheat seeding rate by 50% reduced mustard density 36%, biomass 37%, and seed production 42% (Kolb et al. 2012).

Using narrow row spacing has a similar effect on weed density as increasing seeding rate. Narrow rows allow for quicker canopy establishment. For example, a crop planted in 7.5-inch rows will reach canopy closer sooner than a crop planted in 36-inch rows. In a Maryland study, researchers reported the canopy of corn grown in 15-inch rows closed one week earlier and was more competitive with weeds than corn grown in 30-inch rows (Teasdale 1995). North Carolina researchers studied the effects of row spacing on late-season weed resurgence in soybeans (Yelverton and Coble 1991). Compared to soybeans grown in 36-inch rows, late-season weed resurgence was reduced 43 to 86% by growing soybeans on 18-inch rows. Growing soybeans in 9-inch rows reduced weed resurgence even greater (Figure 10.2).

Leaf design of a crop also affects the ability of a crop canopy to intercept sunlight. Horizontally oriented leaves capture more light than vertically oriented leaves, shading out weeds and discouraging germination of weed seed (Sankula et al. 2004). Under irrigated conditions in Delaware, researchers reported that the use of a corn hybrid with a horizontal leaf design reduced weed density, weed biomass, the amount of sunlight reaching the ground, and weed seed production compared to a hybrid with vertically oriented leaves (Sankula et al. 2004).

Farmers should use these strategies to produce a crop that efficiently captures sunlight while at the same time limits light available to weeds.
Disease and Insect Control

Although diseases, insects, and weeds are often separated into different pest categories, control of one can influence another. Many diseases and insects can defoliate crops. Premature crop defoliation increases light available to weeds. For example, many insects feed on soybean leaves. Holes created in leaves or leaf drop caused by intense feeding of these pests allows more sunlight to penetrate the soybean canopy, which is then available to fuel weed growth. Because of this, farmers may need to control weeds for longer in a crop defoliated by insect pests. For example, Nebraska researchers reported soybean defoliated 60% required weed control for an additional 14 days than soybean defoliated 0% (Gustafson et al. 2006).

Farmers will see a similar trend when encountering diseases that cause defoliation. For example, severe infections of bacterial blight, downy mildew, and soybean rust can defoliate soybeans (Faske et al. 2014). Again, premature defoliation, regardless of the cause, provides weeds with more sunlight to grow and develop. In the absence of disease or insects, a crop grows more efficiently than one subjected to these stresses. From an Integrated Weed Management standpoint, farmers should routinely scout for disease and insects and control these pests when necessary (see Chapter 4: Weed Scouting and Mapping). It is important to remember a healthy crop, free of disease and insects, maintains its competitive advantage over weeds.
Key Points

- Any tactic that improves the ability of a crop to compete with weeds is considered a cultural method of weed control
- Some weeds are easier to control in certain crops; making crop rotation a good strategy for reducing weed populations
- A healthy crop is more competitive with weeds
  - Be sure the fertility demands of your crop are met
  - Ensure your crop is free of disease and insects
- Rapid germination and early-season growth is key to choosing varieties that can better compete with weeds
- Plant crops and cover crops when conditions favor crop development and are not suitable for weeds
- Time of weed emergence varies by species; choose a planting date that gives your crop a jump on weeds
- Quickly forming a dense crop canopy is critical to disrupting weed germination and growth. This can be achieved by the following:
  - Selecting vigorous varieties adapted to local conditions
  - Increasing seeding rates
  - Planting the crop on narrow row spacing
  - Choosing varieties or a crop with leaf orientation that limits light penetration

References

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Chapter 11: Thermal Weed Control

Mark VanGessel

Summary

Thermal weed control relies on intense temperatures to rupture plant cells and rapidly kill plant tissue. This technique is more effective on small plants with an exposed growing point than larger weeds or grasses. This is not a common practice for grain farmers in the Mid-Atlantic region, but has been used effectively in other regions of the US.

Introduction

Thermal weed control using heat, torch type or infrared, has been investigated and adopted by some farmers. Commercial tractor-mounted flaming units are available, but this practice is not widely used in the Mid-Atlantic region. Thermal weed control units produce up to 2000° F, directed at weeds that instantaneously ruptures plant cells and cause rapid desiccation of the exposed tissue.

Flame weeding uses torches containing a nozzle that dispenses a fine stream of propane that is ignited and generates heat (Photo 11.1). Torches are mounted along a tool bar behind the tractor. Torches tend to be highly adjustable to alter height, angle, and direction. In addition, shields are available to confine the heat to increase crop selectivity (Photo 11.2). Flame weeder can be used before as well as after planting to control weed seedling. It can also be used after the crop is large enough to provide a height difference between the taller crop and shorter weeds.

Photo 11.1. Flame weeder set up with torches directing the flame on both sides of the corn. The height, direction and angle of the torches are adjustable. (Photo credit: pinsdaddy-flame-weeding-youtube.jpg)
Calibrating a flamer depends on factors such as propane pressure, operating speed, and arrangement of flame torches. Tractor speed with a flamer falls in the range of three to six mph and typical propane pressure range is 25 to 65 pounds per square inch (psi). A “finger print test” can be used immediately after flaming to determine effectiveness by placing a leaf between the thumb and index finger and pressing firmly. If a darkened fingerprint is visible, it is evidence that cell the cells have ruptured, cell death will occur and rapidly followed by brown dead leaves and stems (Datta and Knezevic 2013).

Results differ by weed species and growth stage. As a general rule, flaming will be most effective when weeds have less than four true leaves. Flaming can kill the aboveground portion of perennial plants, but will not impact underground vegetative structures, or weed seeds in the soil because heat is not transferred into the soil.

Leaf wetness can affect the effectiveness of thermal weed control. Dry leaf surfaces are more likely to be damaged and killed than moist or wet leaves. Flaming should not be done in fields containing high levels of cover crop residue for chance of igniting the dry leaves and stems. Flaming could be used in conjunction with row crop cultivation to flame weeds close to the crop row and then using a cultivator to control weeds between the rows. The advantage of a flame weed over cultivation is that flamers do to disturb the soil and thus reduce the likelihood of causing additional weed emergence.

Not all crops tolerate thermal weeding in the same way. While some crops have a thick cuticle that may provide some protection, others have growing points that are protected from heat damage, and others have stem tissue that is able to tolerate heat.

Flame weeding can be used in corn when the plant is less than one inch tall since at this time corn’s growing point is under ground and surrounded by developing leaves. However, once the first leaves emerge, flaming can damage the plant. Corn is most sensitive at the two- to three-leaf stages. Damage at this stage results in reduced leaf tissue, but this damage seldom reduces final yield. If flaming is done after the five-leaf stage, heat should be kept below the crop canopy. Lower leaves may show heat damage, but the effect does not impact yield (Datta and Knezevic 2013).

Soybeans are not as tolerant of flame weeding as corn since soybeans’ growing point is at the top of the plant and is exposed to the high temperatures. Flame weeding
from the unifoliate to third trifoliate stages is not recommended since soybeans are short and it is difficult to safely direct the heat beneath the crop’s canopy (Knezevic et al. 2014).

Infrared weeders are also available. These are ceramic surfaces, heated with gas, that are positioned to contact the leaves and stems of the weeds. Plant injury and death from infrared units is the same as propane torches. Infrared weeders are used for targeted areas (close proximity to the crop row) rather than broad applications. Heat from microwave units has been researched, but this has not yet been commercialized.

The most common use of thermal weed control in the Mid-Atlantic region is hand-held flame unit with a 10- to 15-pound propane tank are available for small-scale farms. Hot water and hot steam also have been used on small scale, but they are not as effective as flaming weeds.

**Key Points**

- Thermal weed control requires intense heat, thus is highly dependent on fossil fuels.
- Crop safety is species dependent, with corn having more tolerance than soybeans.
- Crop safety is based on selective placement of the flame or heat source to prevent contact with the crop.

**References**


Chapter 12: Cover Crops for Weed Suppression

Jess Bunchek, Steven Mirsky, Victoria Ackroyd, and William Curran

Summary

Cover crops play a significant role in a multi-tactic approach to weed management. As herbicide-resistant weeds have become more prominent, interest in the use of cover crops for weed suppression has increased. In the Northeast, growing interest in organic products has also increased interest in cover crops for their role in weed suppression. Cover crops suppress weeds most effectively when actively growing by out competing weeds for essential resources (light, nutrients, water, and space). Cover crops affect weed germination and emergence by reducing light at the soil surface, lowering soil temperatures, and providing a physical mulch or barrier after they’ve been terminated. Cereal cover crops can also, tie-up nitrogen (immobilize), making it less available for weeds. Furthermore, cover crops can release phytotoxic compounds (allelopathic effect) that impact small seeded weeds. Species selection and management determine the effectiveness of cover crops in weed suppression.

Introduction

A cover crop is a plant that is grown in a cash crop field at times when a field would otherwise be fallow. Cover crops are multifunctional tools that provide a variety of agroecosystem services beyond weed suppression. They support crop productivity and farm profitability, providing erosion control, tighter nutrient cycling, greater water infiltration, and can increase organic matter and biodiversity in the soil when compared to bare ground. The impact of cover crops on weeds is of particular interest, given the time and cost of weed management in all cropping systems, the challenges associated with controlling weeds in organic systems, and the development and spread of herbicide-resistant weeds. In the Northeast, some common winter annual cereal cover crop species include cereal rye, wheat, and triticale. Common winter annual and perennial legumes include hairy vetch, crimson clover, and medium red clover. All of these plants are winter annuals that are established in the fall after corn or soybean harvest. Medium red clover, a perennial, also can be frost-seeded into wheat. Other cover crops, such as sorghum-sudangrass and millet, can be sown in the early spring prior to planting summer vegetables.
Cover crop implementation and management directly and indirectly suppresses weeds at multiple weed life stages (Figure 12.1). Cover crops most effectively suppress weed, when living, by competing with them for space, nutrients, water, and light. Weeds also are directly suppressed at the time of cover crop termination. Weed suppression, particularly for summer annual weeds, is proportional to cover crop biomass levels; as cover crop biomass increases weed biomass decreases. Good ground cover early in the spring affects weed germination and emergence by reducing light at the soil surface and lowering soil surface temperatures (Figure 12.2). Management strategies that affect the ability of cover crops to suppress weeds include cover crop species and mixture combination selection, seeding rate, planting and termination timing and method, and application timing, type, and rate of nutrient inputs. Cover crop management decisions should also weigh the specific weed problem. For example, perennial weeds are less affected than annual weeds by cover crop residues. However, implementing cover crops in conjunction with other cultural practices, such as narrow cash crop row spacing, can have synergistic effects on perennial weed management. Carefully managing cover crops in combination with other cultural practices can manage existing weed populations, slow the development of new weeds, and simultaneously achieve other cover crop benefits important to farmers (see Chapter 10: Cultural Control).
Crop Rotations and Cover Crop Integration

Cover crop species are categorized as follows: fall planted that overwinter, winter kill, biennial and perennial, and summer planted with winter kill. Fall-planted winter-kill cover crops like spring oats and forage radish quickly establish dense ground cover and can control fall-emerging weeds like horseweed and chickweed better than winter-hardy cover crop species that establish more slowly. Fall-planted winter-hardy cover crops like cereal rye and red clover produce most of their biomass between spring green-up and termination, which can control spring-emerging winter annual weeds and early-emerging summer annual weeds. Planting cover crops at high seeding rates and extending the duration they are living in a crop rotation increases early ground cover and smothers competing weeds. Cereal grains are typically planted at one to two bushels per acre, and legumes like hairy vetch and clovers should be

Figure 12.2. Cover crop residue (mulches) have complex effects on the weed seedbank. Cross marks in arrows indicate points at which cover crop mulches affect weed germination or emergence.
planted at about 20 pounds per acre. Seeding rates will vary, depending on climate and soil (Mirsky et al. 2017).

Cover crops can be successfully established throughout the fall. Species selection varies by planting schedule and targeted weeds (Figure 12.3). Winter-kill cover crops like spring oats can produce prolific biomass to control winter annual weeds if the cover crops are planted early in the fall after small grain harvest. Winter-hardy cover crops, such as cereal rye or triticale, better target spring-emerging winter annuals and produce enough residual mulch to help suppress summer annual weeds. If herbicides are an option, the field should be sprayed with a preplant (“burndown”) herbicide before planting late summer or early fall cover crops to better manage winter annual weeds and volunteers from the previous small grain crop and ensure optimal cover crop performance.

Grazing cover crops or harvesting them for forage has several weed suppression benefits. Annual, biennial, and perennial forages or hay crops can serve as both a cover crop and forage and is one of the best strategies for suppressing summer annual weeds, particularly broadleaf species as the frequent mowing/harvesting disturbance prevents weed seed production and exhausts the weed seedbank. Frequent grazing and harvesting of forages can also exhaust the root reserves of problematic perennial weeds.

Intensive cover cropping for forage combined with tillage also can greatly impact weeds. In Pennsylvania, Mirsky et al. (2010) demonstrated that combining tillage with cover cropping during a summer fallow can result in 98%, 85%, and 80% reductions in foxtail, common lambsquarters, and velvetleaf, respectively. Cover cropping strategies that stimulated weed seed germination, where weeds were either suppressed by
grazing/harvesting of covers or through subsequent tillage, results in the greatest weed seedbank declines.

Although they are less common in the Northeast, summer annual cover crops like sorghum-sudangrass and millet can be used as part of an intensive weed management strategy. Research in Illinois reported that Canada thistle shoot density and biomass were greatly reduced over the course of two growing seasons by using either sorghum-sudangrass or a mixture of sorghum-sudangrass and cowpea (Bicksler and Masiunas, 2009).

**Cover Crop Mixtures for Weed Control**

The goal for selecting and managing a cover crop mixture for weed control is to optimize for higher biomass, ground cover, and duration of living cover crop in the field. Plant the mixtures at recommended times with a seeding method, such as drilling, to ensure good seed-to-soil contact and stand establishment. High fertility sites (history of manure use, excess nitrogen from preceding cash crop, and high soil organic matter) fertility will support grass or broadleaf cover crop growth to the possible detriment of legumes as legumes are less competitive in a high nitrogen environment. On sites with lower nitrogen fertility, legumes will compete more readily with other species in the mixture. Regardless, weed suppression increases with greater cover crop biomass levels. Dead or decaying biomass levels have little to no effect on perennial weeds.

Cover crop biomass quality (carbon and nitrogen content) impacts both weed suppression and the performance of the subsequent cash crop. Using cover crop mixtures is a strategy for achieving multiple benefits. For instance, cereal cover crops high in carbon are good at suppressing weeds but can scavenge residual soil nitrogen and further immobilize nitrogen when terminated. A mulch that limits nitrogen availability is good for weed suppression in legumes like soybeans, but is problematic in crops like corn that need a lot of nitrogen. Legume cover crops are a good source of nitrogen for the following cash crop but provide limited weed suppression. In fact, legume cover crops may even stimulate weed emergence and performance (Figure 12.4). Combining grass and legume cover crops, can result in greater biomass levels and
weed suppression while continuing to provide nitrogen for the subsequent corn crop. Work completed in Maryland demonstrated that even low levels of cereal rye, ~20%, in mixture with hairy vetch can maximize weed. Cereal rye provides a trellis for hairy vetch to climb, which keeps vetch off of the soil surface. This relationship delays the start of hairy vetch decomposition, increases the overall carbon to nitrogen ratio, and keeps the soil surface drier than a pure hairy vetch cover crop. Since water and nitrogen stimulate weed emergence, manipulating these factors with cover crops can delay and reduce weed emergence. Cover crop mixtures provide farmers the opportunity to maximize the nitrogen content in a cover crop mixture while not impacting its ability to suppress weeds as a mulch (Figure 12.4). If a producer has multiple cover crop priorities, selecting a mixture of two or more species may be the best choice.

**Cover Crop Termination for Weed Control**

Cover crop termination represents another disturbance throughout a crop rotation and therefore an opportunity to impact weeds. Cover crop termination methods used, depends on the goals and constraints of the cropping system. There are “natural” methods (e.g. winter weather kills a non-hardy cover crop such as forage radish and oats), the chemical method (e.g. herbicide application), and mechanical methods (i.e. tillage, mowing, and roller crimping). Cover crop termination kills weeds currently present in the field and prevents weeds from producing seed.

Tillage and herbicide applications are the most effective means of cover crop termination and have the most impact on emerged weeds. Mowing and roller crimping for cover crop termination are less effective at controlling weeds than herbicides and tillage. Their effectiveness depends both on cover crop species and termination timing. In general, residues that have been roller-crimped suppress weeds better than residues mowed down or left standing.
Prevent Cover Crops from Becoming Weeds

Cover crops add diversity to cropping systems and can be used in combination with other cultural practices to control and slow the development of herbicide-resistant weeds. However, some cover crops like buckwheat, annual ryegrass, and hairy vetch are notorious for becoming weeds themselves if they are not effectively terminated. Such cover crops should be terminated at the appropriate time according to local recommendations to prevent seed production.

However, herbicide-resistant cover crops complicate termination and can become an ongoing weed problem if allowed to set seed. Jasieniuk et al. (2008) reported herbicide resistance in annual ryegrass, also known as Italian ryegrass. To prevent cover crops from becoming weed problems, use high quality certified cover crop seed and known crop varieties. Variety mixtures, variety not stated, bin-run seed, and lower quality seed can potentially introduce a weed problem. Care must be taken to ensure complete control and prevent cover crop seed production. Tillage can completely terminate a cover crop when herbicides are not sufficient. Crop rotations that are incompatible with the life history of the cover crop can also help with long-term management of hard seeded cover crops. For example, planting a small grain like wheat which uses broadleaf herbicides can help provide long-term control for weedy cover crops like hairy vetch.

Cover Crop Mulch for Weed Control

The residue (also known as mulches) of terminated cover crops suppresses weeds by altering environmental cues (light, temperature, oxygen, and precipitation) at the soil surface. For example, light can trigger weeds at or near the soil surface to break dormancy and germinate (Figure 12.2). A mulch that prevents light reaching the soil surface will prevent these light flashes. It also insulates the soil surface and prevents warming of the soil, another germination cue.

Mulches also physically impede germinated weeds from emerging. Numerous cover crops, such as cereal rye and forage radish, release chemical compounds toxic to weeds when decomposing. This process is known as allelopathy. Allelopathic compounds that inhibit weed seed germination are especially active on small-seeded weeds. However, this effect doesn’t last long and can be unpredictable with little effect on large-seeded weeds perennial vegetative structure. Lastly, cover crops with a high C:N ratio (carbon to nitrogen), such as mature cereal rye, temporarily immobilize nitrogen in the soil, which can reduce germination of some weed species that rely on nitrogen availability. This temporary nitrogen immobilization also denies nutrients to existing weed seedlings so that they can’t be competitive with a cash crop.

The more mulch the better for weed suppression. Cereal rye cover crop should produce a minimum biomass of 5000 to 7,500 pounds per acre to provide 75% inhibition of summer annual weed emergence in the Northeast (Mirsky et al. 2011; Ryan et al.)
Unfortunately, cover crops in this region do not consistently produce these high biomass levels, with 4,000 – 6,000 pounds per acre being more typical. Providing livestock manure or fertilizer can enhance cover crop growth, especially following a productive cash crop requiring heavy nitrogen application (such as corn). For example, applying nitrogen (20-40 pounds nitrogen per acre) to a cereal rye cover crop in the early spring to increase biomass production can increase weed suppression.

A Multifaceted Approach

Combining cover crops with cultural or mechanical weed control tactics is an important step toward implementing integrated weed management. A cover crop mulch can be used with high in-row crop population density (i.e., soybeans at 200,000 seeds per acre) and/or narrow-row cash crop planting (i.e., soybeans from 30 to 15 or 7.5 inches), herbicides and tillage to effectively suppress weeds. Ryan et al. (2011) found that increased soybean seeding rates compensated for low cereal rye biomass, ensuring acceptable suppression of summer annual weeds (Figure 12.5). The cereal rye mulch hindered early-season weed growth, giving the high-density soybean planting enough time to close canopy, which hindered weed growth in the middle and late season. In a greenhouse study, the combination of metolachlor (Dual®) and hairy vetch residue enhanced the control of smooth pigweed (Teasdale et al. 2005). Nord et al. (2011) found a postemergence herbicide application to be more effective at decreasing weed biomass than cultivation in soybeans planted into a cereal rye mulch.

Mechanical control tactics also can be used in combination with cover crops. In reduced tillage systems, cultivation has been difficult due to technological limitations. Cultivation is now possible in these systems using high-residue cultivators that neither invert the soil nor drag residue through the field. High-residue cultivators, when used in combination with cover crop mulches, can control weeds in fields with large weed seedbanks or perennial weed infestations. However, cover crop mulches alone are ineffective at suppressing perennial weeds such as yellow nutsedge because they emerge over a prolonged period and have energy reserves beneath the soil that allow the weed to grow back after disturbances (Mirsky et al. 2011).
Key Points

- Living cover crops are the most competitive against weeds, outcompeting weeds for space, light, water, and nutrients.
- The effect of cover crops on weeds varies by species, weed types and time of establishment.
- Perennial weeds are less affected than annual weeds by cover crops.
- Maximize weed suppression by maximizing cover crop biomass.
  - Establish a dense cover crop stand.
  - Delaying cover crop termination increases weed suppression when living and after terminated via higher biomass.
- Implementing cover crop mixtures can meet multiple farmer priorities, such as nitrogen and weed management.
- Both the cover crop termination process and the residue that’s left control weeds.
- Cover crops are not a silver bullet; use them in conjunction with other strategies.

References

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Chapter 13: Pre- and Post-Plant Mechanical Weed Control

Charlie Cahoon, William Curran, and David Sandy

**Summary**

Tillage or mechanical weed control is an important component of integrated weed management. While most primary tillage is used for seedbed preparation, tillage can kill weed seedlings and bury weed seeds. However, it also can stimulate weed seed germination or bring weed seeds closer to the soil surface where they may be more likely to emerge. No-tillage production uses herbicides to replace primary and secondary tillage for controlling emerged weeds prior to cash crop planting. There are a number of benefits to no-till, but increased herbicide use has led to the evolution of herbicide-resistant weeds such as horseweed (or marestail). Some weed species are better adapted to no-tillage than conventional tillage systems and vice versa. Mechanical weed control used after the cash crop is planted controls germinated weed seeds or weeds that have already emerged. The types of tools employed generally kill weed seedlings or small weeds before they are well established and competitive with the crop. The goal is to incorporate mechanical weed control tactics that diversify the cropping system and reduce the potential for herbicide resistance while keeping soil conservation and productivity on the forefront.

**Introduction**

Mechanical weed control generally uses some type of machine pulled by a tractor to physically slice, chop, or uproot small weeds. Hand hoeing or hand removal is also mechanical weed control, but this chapter will only focus on mechanized tactics.

Mechanical weed control is an important component to an integrated weed management system. Prior to the commercialization of herbicides, preplant tillage followed by inter-row cultivation was the primary methods of weed control. In many organic systems, these are still the primary methods used for managing weeds. In continuous no-till systems, it is difficult (but not impossible) to use mechanical cultivation tools and maintain conservation compliance.

Preplant tillage for weed control includes plowing, disking, and field cultivating. These primary and secondary types of tillage can kill emerged weed seedlings and bury weed seeds below the depth that they can successfully germinate and emerge and help
reduce the rate and spread of certain perennial weeds. Inversion tillage, which generally means using a moldboard plow can bury weeds deeper into the soil profile, but can also bring weed seeds to the surface where they are stimulated to germinate. Preplant tillage can help spread vegetative structures of certain perennial weed species. Post-plant tillage including blind tillage and inter-row cultivation can effectively manage annual weeds and help reduce reliance on herbicides. One or two passes with an inter-row cultivator can reduce the total amount of herbicide applied by 50 to 75%, without reducing weed control or soybean yield (Buhler et al. 1992). Mowing is also considered mechanical and may also play a critical role in managing weeds in forage crops or noncrop areas. This will briefly be discussed at the end of this chapter.

**Tillage Prior to Planting (Preplant Tillage)**

Primary tillage implements vary in their role of preparing fields for planting and in weed control method. Tillage by these implements can be divided into two categories: primary and secondary. Primary tillage occurs between harvest of one crop and planting of a second crop. This method is often intense because it breaks open compacted soils, loosens the top soil layer in preparation for secondary tillage, and chops and incorporates crop residue. Examples of primary tillage implements are a moldboard plow and a chisel plow.

Secondary tillage occurs after primary tillage and is shallower and less aggressive than the primary tillage operation. This method is used to crush soil clods left by primary tillage, incorporate fertilizer, create a homogenous seedbed, or firm soil in preparation for planting. Field cultivators, finishing disks, harrows, and cultipackers are examples of secondary tillage implements.

**Tillage Implements**

Many implements have been developed for to control weeds, manage residue, and prepare a seedbed. Below are descriptions of a few tillage implements as defined by *Steel in the Field: A Farmer’s Guide to Weed Management Tools* (SARE 2002).

- **Moldboard plow.** Considered the primary tool for inverting the soil, the moldboard plow consists of a large contoured shank (plow bottom) that cuts both the furrow bottom and wall, flips the furrow slice, and inverts the soil surface (Walters 2017). The plow was developed to bury plant residue and is great for uprooting small and large weeds or completely burying seedlings and seed (Figure 13.1).

- **Chisel plow.** A series of C-shaped shanks spaced 12 inches apart with chisel points or sweeps. The addition of sweeps improves weed control. Chisel plows can shatter hardpan soils and improve water infiltration (Figure 13.2). The addition of 12- to 18-inch wide sweeps improves weed control, but the chisel plow is still not as effective as other implements for controlling weeds.
- **Disk harrow.** Concave blades (known as a disk harrow gang) cut, mix, and incorporate crop residue, create a rough seedbed of overwinter residue for residue-managing planters, or control surface weeds prior to planting (Figure 13.3). Harrows can cut/chop weeds or uproot small weed seedlings. Cutting and mixing action of disk harrows vary with diameter, weight, concavity, and angle of blades and speed at which the implement is pulled.

- **Field cultivator.** Like the chisel plow, a field cultivator is made up of C-shaped shanks, which are less rigid than those of a chisel plow (Figure 13.4). The shanks work along the full width of the implement and two to five inches deep to open up soil or incorporate plant residue. Weeds are uprooted and small weed seedlings are killed. The addition of sweeps help facilitate fallow weed control whereas shovels are used more for field prep.
Effect of Tillage on Weeds

Primary tillage buries weed seeds and vegetative parts and chops weeds into small pieces unable to regrow. Small annual weeds, small seeded species, and simple perennials are more susceptible to tillage than perennials with stolons, rhizomes, or tubers (Klingman 1961). Weed control by tillage is best under dry soil conditions and higher air temperatures. Weeds sliced or uprooted by tillage during these environmental conditions are less likely to recover from tillage operations than weeds tilled when soils are wet and temperatures are moderate.

Secondary tillage disturbs weed roots by loosening or cutting the root system, causing the plants to desiccate before roots can re-establish (Klingman 1961). Because this process involves desiccation, it is most effective when soils are dry and temperatures are high. Similar to primary tillage, small annual weeds and simple perennials weeds are more easily controlled than creeping perennials by secondary tillage. Disking or chopping of rhizomes, stolons, and tubers without additional subsequent weed control may worsen creeping perennial infestations by spreading these reproductive structures.

Farmers should know the weed control limitations of each tillage operation and implement. See Table 13.1 for the relative effectiveness of various tillage implements for control of different types of weeds and weed seed burial. The key to effective weed control with tillage starts with selecting the right tool for the job.

Table 13.1. Effectiveness of tillage implements for control of various weed types based on authors’ experiences. For weed type definitions, see Chapter 2: Identification and Characteristics of Weeds.

<table>
<thead>
<tr>
<th>Tillage implement</th>
<th>Control of existing weeds</th>
<th>Burying annual weed seed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Seedlings</td>
<td>Established annuals or biennials</td>
</tr>
<tr>
<td>Moldboard</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>Chisel</td>
<td>G</td>
<td>Fair</td>
</tr>
<tr>
<td>Disk harrow</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>Field cultivator</td>
<td>G</td>
<td>Poor</td>
</tr>
</tbody>
</table>

Effect of Tillage on Weed Seed

Tillage is almost exclusively responsible for weed seed movement throughout the soil profile, including vertical distribution (Buhler et al. 1997). This movement can affect germination and establishment. While some tillage implements bury weed seed
to a depth not conducive to germination (Table 13.1), other seed may be brought to the surface where sunlight and heat stimulate germination. For example, a single pass of a moldboard plow can initially bury weed seed near the soil surface to the depth of the tillage implement (greater than 6 inches). Tillage systems used over multiple season also can influence the distribution of weed seeds in the soil profile. As seen in Figure 13.2, Wisconsin researchers observed a more even vertical distribution of weed seed after multiple years of moldboard plowing than multiple years of chisel plowing and no-tillage, where weed seed were more concentrated at the top of the soil profile in both systems (Yenish et al. 1992).

![Figure 13.5. Vertical distribution of weed seed as affected by tillage system in a silt loam soil. (Adapted from Yenish et al. 1992)](image)

Seed size determines the depth from which seedlings can emerge. This depth varies by species. Smaller seeds do not have enough energy reserves to emerge from deep within the soil. For example, germination for the small Palmer amaranth and slender amaranth seed is greatest at depths less than one inch (Keeley et al. 1987; Thomas et al. 2006). Sicklepod seed, much larger than slender amaranth, can germinate from deeper than one inch. In a sandy loam soil, Arkansas researchers observed 50% sicklepod germination at a depth of 1.8 inches, and 6% at a depth of 3.9 inches (Norsworthy and Oliveria 2006). Likewise, pitted morningglory, which also has large seeds, germinated from as deep as 3.9 inches (Oliveria and Norsworthy 2006). (See Table 13.2 for optimum emergence depth for several weed species.)
Table 13.2. Optimum emergence depth for several common weeds.

<table>
<thead>
<tr>
<th>Weed Species</th>
<th>Emergence Depth (in)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadleaf signalgrass</td>
<td>0 to 0.4</td>
<td>Burke et al. 2003a</td>
</tr>
<tr>
<td>Common ragweed</td>
<td>0 to 1.6</td>
<td>Guillemin and Chauvel 2011</td>
</tr>
<tr>
<td>Horseweed (or marestail)</td>
<td>0 to 0.20</td>
<td>Nandula et al. 2006</td>
</tr>
<tr>
<td>Palmer amaranth</td>
<td>0 to 0.5</td>
<td>Keeley et al. 1987</td>
</tr>
<tr>
<td>Pitted morningglory</td>
<td>1.6</td>
<td>Oliveria and Norsworthy 2006</td>
</tr>
<tr>
<td>Slender amaranth</td>
<td>0.20 to 0.80</td>
<td>Thomas et al. 2006</td>
</tr>
</tbody>
</table>

Tillage can affect the environmental conditions that are cues for weed seed germination including soil temperature, moisture, oxygen, and light. Tillage will discourage seed from germinating when it places the seed deeper in the profile where temperatures are cool and there is less oxygen and no light penetration. In contrast, tillage can stimulate weed seed to germinate if the seeds are exposed to light and higher oxygen and warmer soil temperatures (see Chapter 3: Weed Emergence, Seedbank Dynamics, and Weed Communities). Palmer amaranth and other pigweed seeds require a flash of light to stimulate germination. Farmers should consider the effects of tillage germination cues for various weed species when considering tillage.

Effect of Tillage Systems on Problem Weed Species

Tillage systems are often classified by the amount of plant residue left on the soil surface and are defined as follows:

- **Conventional tillage.** A conventional-till system disturbs the soil surface across the entire width of the implements and leaves less than 15% residue on the soil surface. Conventional tillage includes multiple operations (often primary tillage followed by secondary tillage). An example is a three-pass system using a moldboard plow for primary tillage and then a finishing disc harrow and field cultivator for secondary tillage.
- **Reduced till.** Similar to conventional till, reduced-till systems disturb the soil across the full width of the implement. However, 15 to 30% surface residue remains after tillage. Chisel plowing without sweeps, a type of reduced tillage, leaves much of the soil surface undisturbed.
- **Mulch-till.** As in conventional- and reduced-till systems, the entire soil surface is tilled, but mulch-till is less aggressive leaving more than 30% residue on the soil surface.
- **Ridge-till.** In the ridge-till system, the cash crop is planted on established ridges that are formed by between-row cultivation to help drain and warm the soil for
better crop emergence. The between-row cultivation is used to build ridges as well as control weeds.

- **Strip-till.** In strip-till systems, a majority of the soil surface is left undisturbed. Strip-till equipment often includes no-till coulters mounted in front of the planter unit to create a narrow tilled zone where the seed is to be planted. This tilled zone helps warm the soil and provides better seed placement.

- **Vertical till.** This is generally shallow tillage used to chop residue from a previous crop in to smaller pieces and distribute it more evenly over the soil surface. Chopping and mixing residue facilitates decomposition, allowing the subsequent cash crop to be planted into more easily. Vertical tillage also can alleviate surface compaction and soil crusting. Vertical tillage implements do not generally control emerged weeds.

- **No-till.** Soil disturbance is minimized in no-till systems. Residue covers 70% of the soil surface. Row cleaners, coulters, and seed-furrow openers create slots for planting seeds in this heavy residue.

The tillage system often dictates what type of weeds can be problematic. In general, reduced and no-till systems may have more problems with perennial weeds and certain small seeded annuals and fewer problems with large seeded annual weeds. Many perennial weeds thrive in no-till systems because their roots are left undisturbed (Glenn and Anderson 1993; Glenn and Heimer 1994). The spread of rhizomes, stolons, and tubers of creeping perennials in a no-tillage system often increases the infestation. In no-till or reduced-till systems, herbicides are usually needed to effectively control perennial weeds. In a Maryland study with no-till corn, herbicides were necessary to adequately control Canada thistle (Glenn and Anderson 1993). Similarly, hemp dogbane and wild blackberry are difficult to control in no-till corn and required
herbicides for effective control (Glenn and Heimer 1994). Likewise, researchers from Pennsylvania reported quackgrass was more difficult to control in no-till than reduced-till corn (Curran et al. 1994). Using tillage in combination with herbicides or other weed control methods is often necessary to deplete the energy reserves of these perennial vegetative structures.

Of the many ways tillage influences the weed seedbank, seed depth in the soil may be most important (Buhler et al. 1997). Weed species that can germinate from the soil surface or shallow depths will flourish in no- or reduced-tillage systems. Farmers in Indiana reported horseweed (or marestail), a small seeded annual was present in 61% of no-till fields compared to 24% of reduced-till fields and 8% of conventionally tilled fields (Loux et al. 2006). In contrast, large-seeded species at or near the soil surface would be less successful (Buhler et al. 1997). Burcucumber, a large seeded annual decreased in density an average of 65% in a no-till system compared with the moldboard plow system (Messersmith et al. 2000). In a similar study, a system using preplant tillage increased burcucumber density by 90% compared to the no-tillage system (Esbenshade et al. 2001). The short-term benefits from tillage were observed in a Maryland study that reported 72% smooth pigweed control in a conventional tillage system using a moldboard plow compared to 63 to 64% in reduced till, and 44% in no-till (Ritter et al. 1985). However, longer term impacts of tillage management might reveal different results. At the end of a nine-year study, Swanton et al. (1999) found common lambsquarters and redroot pigweed were more prevalent in conventionally tilled plots compared with no-till, while large crabgrass was more common in the no-tillage system. Farmers should recognize the effects of their tillage systems on the presence of certain weed species and potential alternative weed management practices needed once species shift.

Tillage and the Weed Seedbank

Stale seedbed systems have long been used for weed control and involve early seedbed preparation using tillage (30 days prior to planting). Tilling the seedbed early stimulates nondormant weeds in the germination zone to emerge, providing the opportunity to control these prior to crop planting (Boyd et al. 2006). These weeds can be controlled by light tillage, herbicides, or flaming, which can be found in some organic systems. Place et al. (2009) reported four passes of a rotary hoe on a stale seedbed reduced weed cover 57% compared to plots that were not tilled.

In a stale seedbed system, light tillage has not been as effective as flaming or herbicides since it often stimulates additional weed germination. In a New York study, glyphosate and flaming in a stale seedbed system reduced weed biomass 46 to 91% compared to the untreated control (Caldwell and Mohler 2001). In the same study, the
rotary tiller, tine weeder, and spring tooth harrow treatments either increased or had no effect on weed biomass compared to the untreated control.

Stale seedbed systems are useful for depleting weed seedbanks. However, the success of this system depends on control of newly emerged weeds. Tillage, herbicides, or other methods must be used to ensure the weed seedbank is not replenished by a few escaped weeds (see Chapter 6: Prevention of Weeds).

Tillage remains an effective tactic for controlling weeds and an important component of IWM. However, farmers should consider the effects of each tillage operation on individual weeds, weed seeds, and weed species dynamics. They should also factor in the environmental impacts of tillage and whether the advantages of tillage outweigh the disadvantages before using tillage equipment in their fields.

**Key Points for Preplant Tillage**

- Tillage was the primary method of weed control prior to herbicides.
- Primary and secondary tillage can be used for control of existing weeds.
  - Primary tillage kills weeds by burying weeds or chopping weeds into small pieces.
  - Secondary tillage disturbs weed roots and leads to plant desiccation.
  - Annual weeds, simple perennial weeds, and small weeds are more susceptible to tillage than creeping perennials and large weeds.
- Weed seed germination and longevity are also affected by tillage.
  - Tillage influences soil temperature, moisture, oxygen, and light, all of which are germination cues for weed seeds.
  - Tillage affects weed seed distribution in the soil profile.
- Weed species and soil weed seedbanks can shift in response to tillage systems employed over multiple seasons.
  - Horseweed and many perennial weeds prefer long-term no-till systems.
  - Tillage alone can spread rhizomes, stolons, and tubers of creeping perennial weeds and worsen infestations.
- Soil weed seedbanks can be depleted via mechanical manipulation of a stale seedbed.
Post-Plant Tillage

The use of cultivation practices after a crop has been planted is primarily used to control weeds is known as post-plant tillage. There are two types of post-plant tillage intended for weed control: blind cultivation and between-row (also known as inter-row) cultivation. Both tactics are more suited for tilled seedbeds, although some post-plant tillage equipment is available for no-till or higher-residue systems. Other reasons for using blind cultivation are to break up soil crust for aeration and to promote faster drying, and incorporating wheat and other small crop seeds that have been broadcast on the soil surface.

Successful post-plant tillage requires diligent monitoring of field conditions and the weather, both of which are important for effective mechanical cultivation. In addition to suitable soil and weather conditions, weed size or growth stage is critical for successful control of the weeds. The need to monitor the weather and soil conditions is critical because there may only be a small window that is ideal or appropriate to cultivate. For grain crops such as corn and soybeans in the Mid-Atlantic region, the months of May and June are when most post-plant tillage takes place prior to crop canopy.

The success of post-plant tillage requires the use of proper equipment. Many different tools have been developed to control weeds after crop planting. Choosing the right equipment and having it properly adjusted will help take advantage of those ideal times to get into the field and achieve G weed control. Relying on mechanical weed control requires thoughtful consideration about time, labor, tractor horsepower needs, implement size and how to budget appropriately. The size of the tractor and implement must match to optimize implement performance as well as energy use. Larger sized implements can save time, but also require a larger tractor with more horsepower. Having multiple tractors available can allow for more than one rotary hoe, tine weeder, and cultivator, to cover all of the ground in a timely fashion. The right piece of equipment will more than pay for itself over time by saving a crop when you only have a narrow window to perform the operation. In addition, having skilled tractor operators that know when crop, weed, and environmental conditions are optimum to achieve effective mechanical weed control is critical.

Considerations for Blind Cultivation

Blind cultivation controls germinating weed seedlings near the soil surface whose roots are above those of the crop. An implement is “blindly” (not worried about driving on the crop rows) pulled through the soil, dislodging small weed seedlings both in the crop row and area between the crop rows. The initial blind cultivation takes place with cash crop germination and root development, but before crop emergence. Subsequent blind cultivation events may continue after the crop has emerged, and are conducted every five to seven days (or as weather allows) for a period of two to four
weeks, depending on the crop. Use of blind tillage to control early weed flushes can be successful if done at the proper time and with precision. In an organic soybean system, North Carolina researchers reported that two passes of a rotary hoe reduced the density of redroot pigweed by 56% and broadleaf signalgrass by 65% (Place et al. 2009). Inaccurate operation can result in damage or removal of young cash crop plants, reducing populations and therefore potentially yield (Martens and Martens, 2005). Some research has reported up to a 14% reduction in corn population from the use of a rotary hoe in tilled systems (Mulder and Doll, 1993; VanGessel et al. 1995; Cox et al., 1999; Mohler et al. 1997). Bates et al. 2012 observed an 8% reduction in corn population from a combination of rotary hoe plus high residue cultivation. The conditions of the soil as well as crop growth stage will dictate whether crop injury is a concern. Increasing the cash crop seeding rate may help overcome some stand loss especially for crops such as corn, where adequate plant population is critical to maintain yield.

Once the crop reaches a certain size, blind cultivation can damage it and emerged weeds become established and too big to control with blind cultivation. In general, blind cultivation can be used from planting to up to 8 inch tall corn and 4 inch tall soybeans (2 to 3 leaves), but make sure that you do not cultivate any bean crop from cracking through the crook stage (Figure 13.7) when they are emerging out of the soil. Cultivation can snap the stem of the bean at this stage and kill the plant.

Some crops are better candidates than others for blind cultivation. In general, crops that quickly develop large taproots after germination, including corn and soybeans, and crop seeds that are planted at a depth of one inch or more will tolerate the blind cultivation. Blind cultivation is not used with small-seeded crops that are planted shallow like alfalfa, clover, and canola because it can reduce the crop population. Blind cultivation is especially effective in controlling small-seeded annuals such as pigweed species and common lambsquarters. It is less effective on large-seeded annuals such as velvetleaf, common and giant ragweed, and annual morningglories because these seedlings often root more than an inch deep in the soil. Blind cultivation is not effective on perennial weeds with well-established roots.

The growth stage of the weed and crop are important factors in determining timing of blind cultivation. The ideal timing for weed control is when weeds are in the white thread stage, known as such because the small seedling resembles a white thread when uprooted (Figure 13.8). In this stage, the weed seed has germinated but has not yet emerged from the soil or developed its first true leaves. Weeds that have emerged are not as easily killed by blind cultivation. The typical window for blind cultivation is 5 to 14 days after the previous tillage operation and careful field scouting will help determine optimum timing. Scout for the weeds’ growth stage by gently digging through the soil with a knife and checking for weed seed germination and white thread stage seedlings (a general rule of thumb is that if the weeds are visible from the seat of the tractor, a rotary hoe will not be effective).
Weather and soil conditions play an important role in the success of blind cultivation. Ideal conditions for cultivation are when the soil is friable (dry to slightly moist but not wet), the weather is sunny and breezy, and no rain is forecast for the next couple days. In dry soil, the cultivator will uproot weeds without creating clods (also known as root balls). If the soil is too wet, the cultivator may uproot the weed with a root ball attached to the roots, which will allow the weed to survive. Sunny and breezy weather help desiccate and kill the weed seedling. Rain soon after cultivation may allow weeds to resprout and survive; but even if conditions are less than ideal, cultivate if possible -- some weed removal is better than no weed control at all.

Cultivation frequency may be determined by the soil and weather conditions, which can prevent timeliness because of rainfall. The ideal schedule is to cultivate once a week as soon as the crop germinates. Typical schedules are two to three blind cultivations followed by two to three between-row cultivations.

Tools for Blind Cultivation

The two primary tools used for blind cultivation in field crops are the flex-tine weeder and the rotary hoe. Both are available in a range of sizes, from 10 to 40 feet, and are typically operated at a speed of 5 to 15 mph.

- **Flex-tine weeder.** The flex-tine weeder (also called tine weeder) is designed to remove weeds inside and outside the crop row (Figure 13.9). It has a series of flexible metal tines that are pulled through the soil to uproot newly germinated weeds in the white thread stage. Dryer soil conditions are necessary to maximize performance. Depending on the implement, crop, and target weeds, tines can be
added or removed and the pressure of each tine increased or decreased (Figure 13.10). This also allows for aggressive cultivation behind the tire pass and light cultivation through the crop row. The downward pressure on the tines, soil moisture, and tractor speed determines effective weed control. Faster tractor speeds increase the vibration of the tines as they are pulled through the soil. The vibrating tines uproot small plants and shake the soil loose from the newly-germinated weeds, bringing them to the soil surface to desiccate and die. Tine weeders perform best in clean tilled seedbeds free of plant residue. Plant residue can get caught in the tines and result in damage to the young crops and ineffective weed control. The tine weeder can be used on a number of crops including barley, wheat, oats, corn, soybeans, sorghum, and sugar beets. In general, tine weeders are less aggressive than rotary hoes.

Rotary hoe. The rotary hoe (Figure 13.11) is a ground-driven implement with a series of wheels with metal spoons radiating out (Figure 13.12) that functions similar to a flex-tine weeder. The spoons are oriented on the wheel so that they enter straight into the soil then emerge from the soil at a slight angle. As the ground speed increases, the tips of the spoons penetrate the soil and then kick out newly-germinated weed seedlings as the spoon exits the soil. Because of this action, the rotary hoe is also most effective during the white thread stage of weed development and avoid cultivating soybeans during the crook stage. Blind cultivation can be resumed in soybeans once cotyledons are completely unfolded. The best time to rotary hoe soybeans is during the afternoon as the plants tend to be slightly flexible and limber during the hotter part of the day. This will lower the risk of the stems snapping. It may be prudent to cultivate a small section of the field initially to monitor the crop and ensure that it is not being damaged. In general, like tine weeders, rotary hoes perform best under dryer soil conditions and with little residue. However, there are different types of rotary hoes that can work in clean tilled, low-residue, and higher-residue environments. With the high residue rotary hoe, the distance between the gangs of hoe wheels is greater to avoid plugging by crop residue. In a Pennsylvania study, equivalent weed control was observed by a vertical coulter/ high-residue rotary harrow compared to glyphosate applied preplant (Bates et al. 2012).
Considerations for Inter-row Cultivation

Tilling the soil between the crop rows to control emerged weeds is known as inter-row cultivation. Only the area between the crop rows is disturbed and the spacing between the crop rows determines the feasibility of using these tools. Adding guidance
systems can allow for greater precision as well as increased speed of operation and reduce the potential for crop damage.

A conventional cultivator is designed for use in low-residue environments with the shanks spaced less than six inches apart. Conventional cultivators are designed for conventionally tilled fields with loose soil and little to no plant residue. The typical operating depth for these units is one to two inches deep, which allows for adequate control of weeds up to three inches tall and sufficiently shallow to avoid bringing up weed seeds from deeper in the soil profile that could subsequently germinate and become established. Inter-row cultivation is less effective in controlling larger, well established weeds. In addition, larger weeds can become entangled in the equipment and result in crop damage and reduced weed control. Typical tractor speed for this type of cultivator is between two and eight mph. Slower operating speeds may be necessary for smaller crops and while faster operating speeds may be tolerated for larger crops that can tolerate contact with the cultivator sweep.

Cultivators are equipped with sweeps (or shovels) attached to the end of the shank on the cultivator unit. The aggressiveness of the between-row weed control is not only determined by the orientation of the shanks on the toolbar, but also by the type of sweep selected. In addition to the sweeps, some cultivators are equipped with disks to control weeds close to the crop rows (weeding disks). Other disks are sometimes added to the cultivator to help form furrows for irrigation or to form ridges or beds (disk-hillers).

There is generally more time and flexibility to perform inter-row cultivation than for blind cultivation since these tools can control larger weeds than flex-tine harrows and rotary hoes. There are a number of different types of shanks and sweeps that are available for between-row cultivation depending how it is used. Shanks connect the sweeps to the body of the cultivator and are designed in various styles. The shanks range from rigid to flexible, allowing the sweep to remain stable or to vibrate through the soil. The type of weed control needed determines what type of shank should be used.

The following list describes the shanks and sweep that are common:

- The Danish S-tine shank cultivates loose and residue-free soil (Figure 13.13). The shank, in combination with a moderate profile crown (middle area of the sweep), will vibrate and mix the soil, uprooting weeds and shaking soil loose from their root systems. This shank controls small seedlings and weeds with shallow root systems.
- The C-shank is more rigid and vibrates less than the S-tine shank, but can still flex around rocks and other obstructions (Figure 13.14). The more rigid shank is designed for harder soil or fields with greater amounts of plant residue. The C-
shank resists flexing and holds the sweep flat to slice through the soil cutting the weeds.

- The V-shaped row crop sweep is a common sweep (Figure 13.15) that can be used on C, S-tine, and straight shanks. Widths available include six to 28 inches. The row crop sweeps slice through the soil, uprooting smaller weeds and cutting root systems of larger weeds. The sweep is designed with a flattened crown, and the angle of the V-shaped wings in relation to the crown is low. As a result, the sweep cuts more than it does mix the soil causing less soil disturbance.

- The Danish tine sweep is another common sweep used in cultivation (Figure 13.16). It was developed for use with the Danish S-tine shank and comes in widths from one to nine inches wide. The sweeps are designed with either a low or moderate profile crown. With the lower crowned sweep, soil mixing and weed control is similar to that of the V-shaped row crop sweep. The moderate crowned sweep offers greater soil mixing and better soil penetration than the wider flatter sweeps.

- A variation of the Danish sweep is the duckfoot, or goosefoot, sweep (Figure 13.17). This type of sweep also was designed for the Danish S-tine and comes in widths from two to seven inches wide. Because of its moderately sloped crown, the duckfoot sweeps offers better soil penetration especially in hard soil. It also is better at uprooting rather than slicing or cutting weeds. The sweep mixes the soil, and the shape of the S-tine allows it to vigorously vibrate, knocking soil from the weed roots, leaving them exposed to desiccate on the surface of the soil.


Figure 13.15. A typical row crop sweep. *Steel in the Field: A Farmer’s Guide to Weed Management Tools.* (SARE 2002)

High Residue Cultivation

Cultivators designed for use in high plant residue environments have been on the market for more than 20 years. These cultivators work in no-till, ridge-till, or tilled fields with a large amount of plant residue. Initially, they were more commonly used in ridge-till systems and designed with a moderate crown and V-shaped wings to throw soil forming a “ridge” at last cultivation. The no-till sweeps on the cultivator were more recently redesigned with a flat crown for less soil disturbance. These types of cultivators typically have one large sweep between two crop rows compared to three or more shanks between crop rows with conventional cultivators.

The three-piece sweep, or high residue sweep, is designed with low disturbance straight shanks (Figure 13.17). As the name implies, the sweep is made up of three components: a replaceable point and two double-edged reversible shares. The point penetrates the soil, while the shares lie flat just below the soil surface and slice weeds, while leaving the surface residue somewhat in place. The shares come in widths ranging from 14 to 28 inches, which determine how close shares travel next to the crop row. These types of sweeps are mounted on either a curved or straight rigid shank.

In no-till operations, the dual gauge wheels in front of the cultivator unit keep the plant residue in place, while a coulter cuts through the residue allowing the sweep to penetrate the soil (Figure 13.18).

Each additional pass with the cultivator will reduce the amount or redistribute any surface plant residue. For ridge-till farmers, an extended wing can be attached to the sweep to create an elevated ridge in the crop row. Ridging wings are usually used during the last pass with the cultivator, when the crops are well established and can withstand soil being thrown into the crop row to form the ridges.
Specialized Cultivator Technology

Several mechanical weed control tools have been developed for higher valued horticultural products. These tools are designed to control small in-row weeds or weeds right next to the crop row in tilled seedbeds. Spyder, torsion, finger, and spring hoe weeder are examples of tools often used in high value crops where effective herbicides are not registered for use or in organic production. These tools generally require height difference between the crop and weeds so transplant vegetables rather than direct seeded crops may be used. These tools require precision, which may mean using smaller equipment or slower operational speeds. These specialized tools are much less common in agronomic crops.

Various guidance systems also are available to ensure accuracy in the operation and allow faster operating speeds. Technology that can allow precision guidance with numerous field operations (including cultivation) is developing quickly. Faster operating speeds reduce operation costs (Paarlberg et al. 1998; Hanna et al., 2000). Bates el al. (2012) operated a six-row high residue cultivator equipped with a hydraulic guidance system at 7 mph compared to the standard 3 or 4 mph greatly reducing the amount of necessary time and labor. More effective weed control and less crop injury from cultivation or other operations can also be reduced with sensory guidance systems (Liebman et al. 2001).
Integrated Systems

Combing inter-row cultivation with herbicides and cultural weed control tactics such as cover crop integration can diversify a weed management program and prevent herbicide-resistant weed evolution. Nord et al. (2011) compared high residue cultivation in an organically managed soybean crop with 30-inch rows to soybeans planted in narrow rows (7.5 inch) with no cultivation. Soybeans were no-till planted into a rolled rye cover crop. Weed biomass generally declined with increasing cereal rye biomass and the added cultivation was necessary when weed density was high, reducing weed biomass by 38 to 62%.

Some studies have investigated reduced herbicide use in conservation tillage systems by applying herbicides in zones or “bands” over the crop row and managing the between-row weeds with cultivation. Integrated weed management research in corn and soybeans from the Mid-Atlantic region reported that high residue cultivation combined with a vertical coulter-rotary harrow and banded herbicide resulted in similar weed control and profitability to treatments where only herbicides were used (Bates et al. 2012). Snyder et al. (2016) reported similar no-till corn yields to herbicide application only treatments in treatments that received banded herbicide plus cultivation. Keene et al. (2016) compared high residue cultivation in both no-till corn and soybeans planted into cover crop residue. Two passes with a high residue cultivator in combination with banded herbicide achieved similar cash crop yield as a post herbicide application. Where herbicide-resistant weeds are already problematic, broadcast herbicide application plus inter-row cultivation may be needed for acceptable weed control.
Mowing as a Method to Suppress Weeds

Mowing is a mechanical tactic that can be used to suppress or control certain weeds. Mowing can play a critical role in managing weeds in forage crops or noncrop areas. Repeated mowing reduces the weed’s competitive ability, depletes carbohydrate reserves in the roots, and can prevent seed production. The success of mowing for weed control depends on the target weed species, timing, and frequency. Mowing is most effective on annuals and biennials that are beginning to flower, rather than in the vegetative stages. When mowed in the vegetative stages, weeds are more likely to recover and regrow and may need to be mowed again. In addition, mowing tends to be more effective on dicots or broadleaves compared to grasses, which tend to be more adapted to cutting. A number of creeping perennials and particularly dicots can also be suppressed with mowing. Successful control or suppression of weeds like Canada thistle depends more on mowing frequency with multiple passes being necessary to prevent regrowth as well as flowering and seed production. A goal when mowing perennials is to deplete carbohydrate reserves in the vegetative portions of the plant by frequent mowing (every 30 days) and to prevent seed production. Simple perennials such as dandelion and the plantains are less susceptible to control by mowing, as they tend to be adapted to low and more frequent cutting.

Several different types of tools are available for mowing:

- **Rotary mowers** are probably the most common and range in size from a common push or self-propelled lawn mower to a brush hog up to larger disk mowers that...
are used to mow hay. These mowers all have rapidly rotating blade(s) that cut plant material a few inches or more off the ground. The sharper the blades, the better the cut. These mowers typically cut plant material into medium sized pieces and either propel them back to the ground or to the side or out the back of the machine.

- **Sickle mowers** also called a reciprocating mower usually has a long bar that is mounted with very sharp triangular shaped blades that rock back and forth to cut plant material. These were the first successful horse-drawn mowers used on farms. They typically cut the plant material near the ground surface leaving the above ground stems and leaves intact. They are less commonly used today likely because of newer designs that are safer and better adapted to multiple environments. There are also walk-behind smaller versions of sicklebar mowers still made by several manufactures for use in commercial, industrial, and residential settings.

- **Flail mowers** have a number of small blades on the end of chains attached to a horizontal axis. They are available in various sizes ranging from a few feet wide up to 20 feet or more. These types of mowers are excellent at cutting larger material and pulverizing it into small pieces. These mowers typically propel the cut material toward the ground to the rear of the mower. Some of the larger models are called “stalk choppers” and are used to mow crop residue after harvest.

- **Reel mowers** also called cylinder mowers are a horizontally rotating cylinder reel composed of helical blades that produce a continuous scissor action. This type of mower is mostly used in the lawn care industry and is less commonly used for mowing weeds.

- **String trimmers** or “weed whackers” are usually hand held or perhaps pushed on wheels and frequently used to mow weeds and other plant material around homes and the farmstead. They are versatile and can be very useful for mowing weeds in uneven terrain.
Key Points

- Mowing is a mechanical tactic that can be used to suppress or control certain weeds.
- Mowing is most effective on annuals and biennials that are beginning to flower, rather than in the vegetative stages.
- Mowing is more effective annual broadleaf weeds compared to grassy weeds.
- Mow perennials is to deplete carbohydrate reserves in the vegetative portions of the plant by frequent mowing and to prevent seed production.
- Simple perennials such as dandelion and the plantains are less susceptible to control by mowing.

Illustrations by John Gist. Reprinted from "Steel in the Field: A Farmer’s Guide to Weed Management Tools" with permission from the national outreach office of USDA’s Sustainable Agriculture Research and Education (SARE) program. For more information about SARE or sustainable agriculture, see www.sare.org

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Chapter 14: Harvest Weed Seed Control

Annie Klodd

Summary

Weeds that escape in-season control will mature and return seeds to the soil in the fall, unless they are managed prior to seed shed. Harvest weed seed control (HWSC) recently emerged from Australia as a way to address weed seeds retained on standing weeds at the time of harvest by either killing or removing escaped weed seeds during crop harvest. There are several HWSC methods, three of which are currently being tested in the United States. Ongoing research will reveal the level of effectiveness of these techniques on problem weeds in the US.

Introduction

Weeds that escape in-season control will mature and return seeds to the soil in the fall, unless they are managed prior to seed shed. Harvest weed seed control (HWSC) recently emerged from Australia as a way to address weed seeds retained on standing weeds at the time of harvest by either killing or removing escaped weed seeds during crop harvest. There are several HWSC methods, three of which are currently being tested in the United States. Ongoing research will reveal how effective these techniques are on problem weeds in the US.

How Escaped Weeds Occur

Whether in conventional or organic crops, weeds often survive in-season control and continue to mature through the end of the season. These weed escapes can occur for several reasons. For instance, if herbicides with low efficacy for the weed species present are applied, or if the herbicides are applied when the weeds are too large, weeds will likely survive and produce seed. Escapes also occur if tillage and cultivation efforts do not control weeds. The rapid rise in herbicide-resistant weeds also increases the likelihood of weeds that may escape in-season control methods.

When these weeds escape, there is a high likelihood they will mature and produce seed, and make additions to the soil weed seedbank. These seeds can last many years and impact crop production for years to come (Walsh and Powles 2014), with major weed management challenges and reduced yield for several years (or decades in the case of some species). Some prolific weed species, such as Palmer amaranth,
produce large numbers of seeds and can develop significant seedbanks from just a few plants.  

**Herbicide resistance and escaped weeds.** The spread of herbicide-resistant weeds has raised concern over escapes in many agronomic regions, including the Mid-Atlantic (see Chapter 7: Weed Resistance to Herbicides). Resistance to herbicide modes of action limits effective control options, raising the probability of weeds surviving commonly used herbicides. Throughout the US, farmers concerned about seed production have resorted to hand removal of escaped weeds. In Australia, the widespread challenge of herbicide resistance in several problem weeds has resulted in the development of innovative mechanical methods to control them and their seeds during harvest.

**Harvest Weed Seed Control**

Harvest weed seed control (HWSC) includes several mechanical and thermal methods that kill or remove weed seeds from plants still standing during harvest operations. Australian farmers and weed scientists facing overwhelming herbicide-resistance developed these innovative methods.

If weeds survive pre-season or in-season control and are mature at harvest-time, farmers may employ HWSC methods to prevent these weeds from dropping seed. If farmers can stop new weed seeds from entering the field’s soil seedbank each year, the weed seedbank can be depleted, and problem weed populations drastically reduced over time (Newman 2014). Killing seed in the field and decreasing the potential weed seedbank, also helps prevent the spread of weeds to other fields.

HWSC is not intended to replace other weed management practices such as herbicides, tillage, or cultural tactics. Rather, it is meant as a clean-up or salvage technique to manage weeds that survived these in-season practices, so that they do not contribute to future weed problems.

**Current adoption of HWSC.** Research and development is ongoing to evaluate HWSC’s potential effectiveness in the Mid-Atlantic and other US regions. Currently, these new technologies are widely adopted in Australia. Australian weed scientists found that various HWSC techniques (described below) killed 75-99% of weed seeds at harvest (Walsh et al. 2013). All HWSC techniques are dependent on seed remaining on the plant at harvest time. For success, harvest needs to occur as soon as the crop is ready, but before weeds shed seed. Because the use of these techniques is mostly limited to Australia, almost all of the information we currently have about HWSC is based on experiences of Australian farmers and weed scientists. In the US, HWSC trials have been conducted in Arkansas, and a multi-university research project began in 2016 to examine HWSC techniques. This project, funded by the USDA Agricultural Research Service, will continue for several more years.
Harvest Weed Seed Control Techniques

*Narrow windrow burning.* Narrow windrow burning (NWB) places combine residues into a narrow windrow, which is burned to kill any weed seeds it contains within. The windrows are formed by directing the chaff through chutes built onto the back of the combine (Walsh and Newman 2007) (Photo 14.1). This method provides more effective weed control than burning the whole field. Because concentrating the chaff into a narrow windrow creates high temperatures that d weed seeds (Schwartz et al. 2016) (Photo 14.2).

While this technique has shown success in Australia and in Arkansas, it is not known whether it will be a viable HWSC strategy in the Mid-Atlantic. Its success is dependent on state-level burn regulations and timing of rainfall. Several years of testing at the University of Arkansas show promising results, and 30% of farmers in Australia use it as an effective method to control multiple-herbicide-resistant ryegrass. In Arkansas, NWB testing has shown 100% kill of Palmer amaranth, morningglory, johnsongrass, and barnyardgrass seeds. Over three years, this resulted in a 73% reduction in escaped Palmer amaranth plants and a 62% reduction in the Palmer amaranth seedbank (Norsworthy et al. 2016). Trials in Australia have shown that 99% of annual ryegrass and wild radish seeds were killed in wheat, canola, and lupin stubble windrows (Newman 2014).

There are several ways farmers can optimize their technique for successful NWB. Harvesting as close to the ground as possible will put more crop residue in the narrow windrow, increasing the fuel for burning. High temperatures are key, but the temperature and length of exposure needed to kill seed can differ among weed species. For instance, 10 seconds at 400°F is sufficient to kill ryegrass, while 30 seconds was needed to kill radish seeds. Australian NWB experts recommend burn temperatures reach at least 752°F for 30 seconds at any given spot in the windrow in order to completely kill seed. The speed of the burn is important, a slow burn increases flame temperatures. Denser windrows also increase temperatures. The burn must reach the soil surface below the windrow to contact ground-level seeds. Because different crops burn at different rates, burn protocols in the Mid-Atlantic should be designed to meet the needs of the crops in our region.

Challenges to narrow windrow burning include complying with burn regulations, modifying the back of the combine to eject chaff in narrow windrows, isolating the burn area, and harvesting at the right speed for forming dense windrow. Poor weather conditions like low temperatures, high humidity, high winds, and rainfall at the time of burning affect the success of a burn (Newman 2014). In the Mid-Atlantic, autumn rainfall may create excess moisture, challenging the ability to effectively burn windrows.
Photo 14.1: Chaff being formed into windrows during harvest in preparation for narrow windrow burning in a western Australian wheat field. (Photo credit: R. Messina and A. Messina, ABC News Australia)

Photo 14.2: A narrow windrow burning in a Virginia Tech research project. (Photo credit: A. Klodd)

**Chaff carts.** A chaff cart is a large bin that follows the combine during harvest, collecting the weed seed-containing chaff ejected from the combine (Photo 14.3). The cart collects chaff, husks of seed, which would otherwise be blown back onto the field, removing weed seeds from the field and allowing them to be disposed. When using a chaff cart, the straw fraction, dried crop vegetation, is typically still spread across the
field. For success, the combine must be adjusted (and in some cases modified with baffles) so that weed seeds exit the combine in the chaff fraction and not in the straw fraction.

The collected chaff is then emptied into a pile either on or off of the field. The pile can be burned or composted to kill weed seed. Burning in a large pile can create temperatures high enough to kill the weed seed and prevent the spread of weed seeds to other areas. As in narrow windrow burning, feasibility of the burning method in the Mid-Atlantic partly depends on state and local burning regulations. Proper composting methods create internal temperatures hot enough and for long enough time periods to kill most weed seeds.

The Australian Herbicide Resistance Initiative tested chaff carts on several commercial harvesters and found the carts collected 75 to 85% of annual ryegrass seeds that entered the combine during harvest (Walsh and Powles 2007). This Australian species of ryegrass is different than the species we see in the US so chaff cart results on this weed in our fields may differ from those reported in Australia.

Chaff carts provide a relatively simple method of HWSC compared, because highly specialized equipment is not required. However, one challenge of chaff carts is that their size and weight add to already large harvest equipment. Turning on small fields may be difficult, and soil compaction potential is greater. Additionally, the need to dump the chaff cart contents periodically will slow harvest. At this time, there are very few companies in the United States that make chaff carts.

Photo 14.3: A chaff cart pulled behind a combine in Australia. (Photo credit: M. Walsh, Australian Herbicide Resistance Initiative)
**Harrington Seed Destructor.** The Harrington Seed Destructor (HSD) is a cage mill system that grinds the weed seed-containing chaff, which kills weed seeds, and then discharges residue onto the field (Photo 14.4). The HSD is designed and manufactured in Australia by deBruin Manufacturing. In the US, preliminary data from Illinois found the HSD killed nearly 100% of seeds that enter the cage mill (weed species in this study included common waterhemp, common lambsquarters, giant foxtail, velvetleaf, morningglory species, giant ragweed, and common cocklebur) (Figure 14.1 and Photo 14.5). It appears that larger seeds (giant ragweed, common cocklebur) remained intact at a higher percentage than smaller seeds. Furthermore, seeds sent through the HSD and remained intact, were buried, but very few were viable the following spring. In Australia, extensive testing has found that the HSD kills 95% of wild radish, wild oat, brome, and annual ryegrass seeds (Walsh et al. 2013).

Photo 14.4: flow of chaff and straw through the combine and the Harrington Seed Destructor.
Figure 14.1. Percent potential viability of seeds of seven common weed species after going through a stationary Harrington Seed Destructor (HSD). Seeds were visually inspected and labeled fully intact or potentially viable if seed coat was mostly intact. For each species tested, the HSD rendered at least 96% of the weed seeds nonviable. (Davis, 2016, personal communication).
Photo 14.5: Pigweed seeds exhibit significant damage after HSD processing in Urbana-Champaign, IL, rendering most seeds nonviable. (Photo credit: A. Davis, USDA-Urbana)

Effect of HWSC on weed species in the Mid-Atlantic Region. Ongoing trials evaluate the potential of HWSC for controlling weeds of concern in cropping systems of the Mid-Atlantic region. Because HWSC targets weed seeds at harvest-time, best control is obtained for species that keep their seeds on the plants closer to crop harvest, and have shorter seedbank lifespans. In the Mid-Atlantic, some of the herbicide-resistant weeds of highest concern are Palmer Amaranth, common waterhemp, horseweed, common ragweed, and common lambsquarters, which vary in seed-drop timing and seedbank lifespan (Figure 14.2).
Researchers note that HWSC will be most successful on weed species that wait to drop their seeds until after harvest-time. Research in Arkansas found that 95 to 100% of Palmer amaranth and common waterhemp seeds remained on the plants at soybean harvest (Schwartz et al. 2015). These results may not be the same in the Mid-Atlantic, where harvest often begins later in the fall. Research is currently ongoing in the Mid-Atlantic and other regions to learn seed drop time in relation to crop harvest for problem annual weeds like common ragweed and common lambsquarters. Weed species that drop their seeds earlier and have a lower percentage on the plant at the time of harvest, enable more seeds to enter the soil before HWSC is implemented to kill them.

Figure 14.2: The difference in weed species that retained their seeds until soybean harvest.
Key Points

- Failure to control weeds early in the season leads to “escaped” weeds that drop seeds, often in the fall, and contribute to the soil seedbank.
- Depleting the soil weed seedbank is an important measure to manage weed pressure in a field.
- **Harvest weed seed control** (HWSC) is a new method to kill or remove weed seeds during harvest-time and can be accomplished in using a variety of tactics.
- HWSC is most successful when harvest occurs as soon as possible and target weeds are small seeded and short-lived in the seedbank.
- **Chaff cart:** this cart travels behind the combine during harvest and collects weed seed-containing chaff.

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Chapter 15: Coordinating Integrated Weed Management Tactics

Mark VanGessel

Summary

Integrated weed management involves a very broad range of tactics, some directly impacting weeds and others having an indirect effect. The goal is to lessen the over-reliance on any one tactic that allows one species to increase more than other species, including selecting herbicide-resistance populations. There are a number of potential approaches and successful programs will be site specific.

Introduction

Successful IWM programs will be site specific, depending on many factors, including weed species in the field. Integrated tactics such as prevention, scouting, and identification are all important for implementing successful IWM strategies, but none of them directly kill weeds. Other tactics such as crop rotation or cultural practices are often selected for agronomic reasons, but can have important effects on weed management. In many cases, these nonchemical approaches will not replace herbicides; they supplement herbicides to provide more consistent control and reduce the risk that a few plants might survive and produce seeds; seeds that can create problems in future years. Some tactics like cultivation or herbicides are used with the main purpose of killing weeds. More clearly understanding how these tactics link together is important.

Each farmer has to evaluate what is feasible for a particular field, possibly prioritizing fields that may need a more comprehensive approach to IWM (or higher level of IWM utilization). Then determining appropriate mechanical, cultural, chemical, and biological tactics, and evaluating the ability to implement these tactics. It is not possible to discuss all the potential IWM scenarios, but analyzing a specific situation provides better understanding of the relationship among various IWM tactics.

Scenario

Scouting history from the past three years indicates the field has triazine-resistant common lambsquarters, acetolactate synthase-resistant (ALS-R or Group 2-resistant)
redroot pigweed, velvetleaf, and large crabgrass. For the upcoming season, the field will be planted with corn.

**Prevention and scouting.** Prevent any new species or herbicide-resistant biotypes from entering the field. This includes cleaning any equipment used in fields with hard-to-manage weeds before leaving that field. When purchasing used equipment or having custom work done on your farm, be sure the equipment is inspected and cleaned prior to delivery to prevent unwanted weed species from being transported with the equipment.

Purchase certified corn seed and find a reputable supplier of cover crop seeds. The cover crop seeds should have been grown in weed-free fields, and the combine and seed handling equipment is cleaned thoroughly to exclude foreign matter and weed seeds.

Triazine herbicides will not control common lambsquarters and ALS-inhibiting herbicides will not control redroot pigweed because of the presence of herbicide-resistant biotypes. Otherwise, these biotypes will respond the same as the susceptible biotypes to other tactics, such as cultural and mechanical weed control as well as other herbicide groups. Emergence patterns, growth rates, and competitiveness for the herbicide-resistant biotypes are the same as herbicide-susceptible biotypes.

Table 15.1. Relative advantage of various tactics for weed management. Since IWM is a continuum from little to comprehensive, three levels of IWM utilization are described. The scenario is based on corn planted in the current season and weeds of concern are triazine-resistant common lambsquarters, acetolactate synthase-resistant redroot pigweed, velvetleaf, and large crabgrass.

<table>
<thead>
<tr>
<th>Tactics</th>
<th>Level of IWM used</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Crop rotation</strong></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Corn last year</td>
<td></td>
<td>-/+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soybeans last year</td>
<td></td>
<td></td>
<td>+</td>
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</tr>
<tr>
<td>Wheat fb soybeans last year</td>
<td></td>
<td></td>
<td></td>
<td>++</td>
</tr>
<tr>
<td><strong>Tillage</strong></td>
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</tr>
<tr>
<td>Chisel plow</td>
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<td>-/+</td>
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<td></td>
</tr>
<tr>
<td>No-till</td>
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<td></td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td><strong>Cover crop</strong></td>
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<td></td>
</tr>
<tr>
<td>None</td>
<td></td>
<td>-/+</td>
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<td></td>
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<tr>
<td>Rye - terminated April 1</td>
<td></td>
<td></td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Rye - terminated 10 days before planting</td>
<td></td>
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<td></td>
<td>+++</td>
</tr>
</tbody>
</table>
Integrated Weed Management

Cultural

<table>
<thead>
<tr>
<th>Timely planting</th>
<th>+</th>
<th>+</th>
<th>+</th>
</tr>
</thead>
</table>
| Fertility
| all at planting | - |
| side-dress application | ++ | ++ |
| Hybrid selection³
| allows sunlight infiltration | -/+ |
| provides dense leaf canopy | + |
| provides late-season shading | ++ |

Herbicide⁴

| Reduced rate PRE² fb glyphosate | - |
| Full rate PRE fb glyphosate + Callisto⁰+ atrazine | +⁵ | ++⁵ |

Inter-row cultivation

| None | -/+ | -/+ |
| One or more cultivations | ++⁶ |

Late-season Weed Control

| None | - |
| Hand pulling | ++ | ++ |

Harvest time

| Delayed harvest (2 wks past 15% moisture) | - |
| Harvest fb mowing stalks | + |
| Harvest fb wheat planting⁷ | ++ |

¹Symbols: -= disadvantage; -/+ = neutral; += some advantages; and ++ = many advantages.
²Abbreviations: fb = followed by; PRE = preemergence; wks = weeks.
³Corn hybrids differ in their ability to produce shade, depending on maturity date, leaf architecture, stay green, and dry down. Hybrids with horizontal leaves provide more shading and provide better weed control than hybrids with upright leaf architecture. Hybrids with better stay green ratings provide more late-season shading.
⁴Level of IWM related to herbicides is very dependent on herbicides used last season. If corn was planted last season, then avoid using the same herbicide program again.
⁵Callisto⁰ (mesotrione) is an example of an herbicide mechanism of action that is very effective on common lambsquarters and redroot pigweed. A high level of IWM would ensure that Callisto⁰ is not used in consecutive years.
⁶Additional equipment may be required.
Emerged weeds are controlled with plowing or effective nonselective herbicide prior to planting wheat.

*Weed emergence.* Knowing when weeds begin to emerge and how long emergence occurs often determines the success of weed management tactics. Common lambsquarters and redroot pigweed begin to emerge in early spring and will continue emerging throughout July, although the majority of plants emerge by early June. Velvetleaf has a shorter weed emergence period, starting shortly after redroot pigweed and common lambsquarters. By late May, the emergence of most velvetleaf is complete. Large crabgrass emergence begins later (late May) and continues through late July. There is not a single time that is ideal for controlling all four of these species. The long emergence period of large crabgrass will require that the ground is shaded by crop canopy or cover crop residue, or a postemergence herbicide with residual control is used.

**Crop Rotation and Cultural Weed Management**

The first step is considering the crop planted last season. Rotating between different crops allow for a more diverse IWM approach. IWM programs for a second year of corn needs to consider tactics that differ from last year. If soybeans were planted in the previous last season, there will be different fertility programs and different planting dates that will increase the diversity of IWM. Corn is planted earlier than soybeans which allows for tillage or herbicide applications to occur at different times and target weeds that germinate at different times of the season.

Even more impactful is if last year the field was winter wheat followed by double-cropped soybeans. This rotation would have provided a dramatically different planting date that allowed early emerging weeds to have been controlled at time of soybean planting with a nonselective herbicide (i.e. glyphosate, paraquat or glufosinate) and then a short growing-season that would have minimized the potential number of weed seeds produced. The narrow row spacing of small grains would provide maximize shading early in the summer, when low IWM utilization would be relying on herbicides for weed control. Using winter wheat and soybeans result in fertilizer applications at different times of the year. For instance, winter wheat fertilizers are applied in early spring well before most summer annual weeds begin to emerge and since no nitrogen is applied to soybeans, summer weed growth is slowed or limited by lack of nitrogen availability.

Crop rotation improves crop growth more than the use of continuous cropping, and this in turn increases crop competitiveness with weeds. In addition, crop rotation often allows for use of additional herbicides and different herbicide mechanisms of
action. While monocultures can incorporate different herbicide mechanism of action, crop rotation often provides even a wider selection of herbicide groups.

Corn hybrids differ in their ability to develop competitive crop canopies that prevent sunlight from reaching weed seedlings. Characteristics such as leaf architecture (upright versus horizontal), stay green, and drydown all affect how late into the season the crop canopy can intercept sunlight and prevent weed growth. A moderate and high level of IWM utilization would consider crop hybrid selection based on these characteristics and select hybrids with horizontal leaves and higher stay green ratings and quick drydown traits. These stay green and drydown traits will maximize sun interception for as long as possible.

**Tillage.** The effect of tillage on weeds is difficult to predict. If the field has been tilled annually or every other year, then planting corn with conventional tillage this year would likely increase the germination and density of all the weed species in this field. Using no-till for this season would reduce overall weed emergence. However, if the field has been managed under a no-till system, then weed seeds are concentrated in the upper one to two inches of the soil rather than evenly distributed throughout the soil. As a consequence, chisel plowing or no-till this year may lead to higher weed densities than if the field was moldboard plowed. Chisel plowing results in soil gas exchange and seed coat, and at the same time it does not bury seeds so it will likely lead to a large flush (or cohort) of seedlings right after tillage. No-till will often lead to a longer emergence period than if tillage was done. Moldboard plowing will bury seeds at least three inches deep, where they are less likely to emerge and become established (see Chapter 13: Pre- and Post-Plant Mechanical Weed Control for more information on the effects of soil tillage on weed emergence and seedling establishment).

Since common lambsquarters, redroot pigweed and velvetleaf are early emerging species, tillage as a stale-seedbed approach can reduce weed density (see Chapter 13: Pre- and Post-Plant Mechanical Weed Control). Plowing and disking the soil two to three weeks prior to planting corn will provide stimuli for weed emergence with a final field cultivation just prior to planting to eliminate all emerged weeds. This strategy is likely to be less effective on large crabgrass since it is a later emerging species.

Cultivation can increase the level of IWM and is compatible with crop rotations and herbicides. Cultivation is an effective tool that can control most annual weed species and affects all but a narrow band of soil where the crop is planted. Cultivation can disrupt herbicide layers if the cultivator sweeps are set lower than the herbicide layer. It can also result in additional weed flush due to soil gas exchange, reducing soil crusting, and/or weed seed coat scarification. Cultivation is generally considered an option only with conventional tillage, but cultivators are available to control weeds in no-till, including if cover crop residues are present.
Cover crop. Cover crops often will provide competition to reduce the number, size, and vigor of winter annual weeds and early-emerging summer annuals such as common lambsquarters and redroot pigweed. Cover crop effectiveness depends on the species planted and presence of conditions that favor rapid early growth. Slow-growing cover crops such as hairy vetch or crimson clover are not as effective in competing with winter annual weeds as rapidly growing cover crop species such as cereal rye. If enough cover crop residue (dead leaves and stems) is present after termination, it can improve summer annual weed control by preventing light from reaching the soil and hindering further weed germination and seedling growth.

The later cover crops grow in the spring, larger amounts of lignin are produced and the cover crop residue is more resistant to degradation on the soil surface. Cover crops terminated seven to ten days prior to cash crop planting will be more effective in suppressing later emerging weeds such as large crabgrass than a cover crop terminated three weeks or longer prior to planting.

Terminating cover crops can kill emerged weed seedlings. Herbicides often used to terminate cover crops, such as glyphosate or paraquat, will provide control of emerged weeds as well. Mowing or using roller-crimping to terminate cover crops is often less effective for control of small or short weeds, which may grow rapidly once the cover crop is terminated. In addition, mowing will cut and shred the cover crop into small pieces that are also likely to break down rapidly and not provide suppression of later emerging weed species.

Chemical weed control. Herbicides are commonly used for weed control. As discussed in Chapter 8: Chemical Control, the information collected while scouting can be used to tailor an herbicide program for the weed species present, determine when to treat the field, and ascertain if the treatment was successful. Since this field has species that emerge both early (common lambsquarters and redroot pigweed) and late (large crabgrass), herbicides that provide residual control will improve overall weed control. Since two weed species are herbicide-resistant, herbicide options are limited. While common lambsquarters are resistant to triazines, this herbicide group will likely be used for corn to control redroot pigweed and velvetleaf. Since ALS-resistant redroot pigweed can be controlled by common corn herbicides and a number of weed species have developed resistance to ALS-inhibiting herbicides, moderate and high IWM utilization would not use ALS-inhibiting herbicides in corn. This would limit the selection pressure of ALS-inhibiting herbicides by using them only in soybeans.

Large crabgrass has a long germination period and may require a postemergence herbicide. Scouting will be important to determine if a postemergence spray is necessary and to ensure the application is made before the large crabgrass becomes too tall for effective control.

Late-season weed control. Low IWM utilization would not use any additional weed control after “layby” (time when crop canopy starts to shade the entire soil surface). A
moderate level of weed control would apply an appropriate herbicide with drop nozzles to control late emerging weeds that could compete with corn and produce a lot of weed seed. A high level of IWM utilization would hand pull patches of velvetleaf and lambsquarters before they produce viable seed. Both of these species produce seeds that persist for over 10 years in the soil seedbank, hampering weed management for many years.

Harvesting the corn in a timely fashion can influence late-season weed growth and limit weed seed production. Once the corn crop starts to dry down, sunlight is able to reach shorter weeds and allow them to regrow and produce additional weed seeds. A high level of IWM utilization would harvest fields as soon as grain reaches an acceptable moisture level followed by mechanical or chemical control of emerged weeds to prevent further weed seed production.

If weed management was not successful and common lambsquarters and velvetleaf produced mature seeds, a high level of IWM would limit their spread. An example is harvesting the infested portion of the field last, and then thoroughly clean the combine before it leaves the field to keep the infestation confined.

Scouting at harvest is critical for high level of IWM to determine which weed species are present and which ones produced viable seed. Each year review and evaluate the success of achieving zero weed seed production and make modifications based on scouting information.

### Key Points

- Including multiple, effective weed management tactics is the cornerstone of managing herbicide-resistant weeds and reducing the risk of selecting for additional herbicide-resistant biotypes.
- Understanding the compatibility of various tactics will allow for a higher level of IWM utilization.
- IWM can improve the consistency of chemical weed control.
- While many cultural and tillage practices may be used solely for agronomic regions, recognizing the benefits they practices may have will allow for a more comprehensive approach to IWM.
**Glossary**

Adjuvant- a product typically used with postemergence herbicides to improve herbicide activity, including nonionic surfactants, crop oil concentrates, or methylated seed oil.

Between-row cultivation – cultivating or tilling to control weeds after the crop has emerged between the crop rows.

Biennial- a species that requires two years to complete its life cycle, and the life cycle begins with seed germination and emergence.

Biological weed control (biocontrol) - the deliberate use of the weeds natural enemies to reduce the density to a tolerable level. Natural enemies are usually insects or pathogens, but grazing animals are used as biological weed control in some situations.

Biotypes- a group of individual of plants, within a species, that has distinct genetic variation, including a trait for herbicide-resistance.

Blind cultivation or blind tillage – shallow tillage performed shortly after planting the cash crop for weed control. Disturbs 100 percent of the soil surface without regard to crop rows. A flex-tine harrow and rotary hoe are common tools used for blind cultivation.

Bulb- underground perennial food storage organ, containing numerous overlapping leaf scales.

Carabids – another term for ground beetles that are commonly associated with seed predation.

Chaff- the small pieces of crop and weed residue, separated from the harvested grain and typically are blown out of the back of a combine.

Cohorts- all weeds that emerge within a short time period, typically after tillage, planting, or other effect that stimulates weed emergence.
Conservation biocontrol- manipulating a cropping system to increase the populations of natural weed suppressing organisms. These are typically insects.

Conventional tillage- the use of inversion tillage such as a moldboard plow or sometimes a chisel plow to create the seedbed prior to planting. Leaves little exposed plant residue on the soil surface.

GM crop (or traited crop)- which are crops developed with genetic engineering, a more precise method of plant breeding. This procedure differs from other plant-breeding techniques by enabling specific, predictable changes to be made to the plant.

Critical weed-free period- the time period the crop needs to be free of weeds to show no detrimental effect on yield

Crook stage – The stage when a bean seedling is emerging from the soil and only the stem (hypocotyl) is exposed and the cotyledons are still beneath the surface.

Crop rotation (rotational crops)- the sequence of crops planted. This can include more than one crop per year or crop sequence for multiple years.

Desiccate – to remove the moisture from something or dry out.

Dispersal- to spread.

Dry down- the physiological process of a crop losing moisture after it has reached full reproductive stage.

Fallow- a period during a crop rotation where no crop is grown; generally done to control weeds and/or conserve soil moisture.

Ground beetles – A group of insects also known as carabids associated with predation.

Growing point- the region of the plant where the plant tissue is actively growing and results in larger plants. For broadleaf plants, this is typically at the top of the stem, while for grasses it is at the base of the stems.
Growth stage- definite periods of plant growth during its life, marked by number leaves, plant growth, or plant development.

Guidance systems– systems use mechanical, hydraulic and electronic methods to detect equipment such as a cultivator movement in relation to the crop row, and then move the tractor, the hitch or the tool to restore the desired alignment.

Harrow - an agricultural implement consisting of many spikes, tines or discs dragged across the soil.

High residue – cropping systems that maintain crop residue on the soil surface often associated with no-till or conservation tillage.

Inter-row cultivation- cultivating or tilling to control weeds after the crop has emerged between the crop rows.

Knockdown- term for non-selective herbicide application.

Mechanism of action- the specific enzymatic activity that an herbicide targets to kill a plant.

Minimum tillage- generally synonymous with reduced tillage.

Mode of action- effect that an herbicide has on plant growth. These are typically visual symptoms observed within days or weeks of herbicide application.

Nonselective- an herbicide that generally controls a large number of plants, including crops.

Perennial- a plant that produces vegetative structures that allow it to live for more than two years.

Postemergence- refers to an herbicide application timing after the plants have emerged from the soil.

Post-plant tillage – tillage or cultivation that takes place after the crop is planted; primarily used for weed control.
Predation – A hunting organism or predator attacks and feeds on another organism or the prey. As an example, a ground beetle is the predator and weed seed is the prey.

Preplant tillage – Tillage that occurs prior to planting the crop such as plowing to prepare a seedbed.

Primary tillage – The first tillage operation that occurs, such as plowing after a crop is harvested and prior to planting the next crop.

Propagules- structures by which new plants develop, includes seeds, rhizomes, stolons, bulbs, etc.

Reduced tillage – Uses less intensive tillage tools such as a chisel plow that generally do not invert the soil. A soil conservation practice used to create the seedbed prior to planting.

Refuge - a place of shelter, protection or safety.

Rhizome- horizontal, underground stem capable of producing stems and roots at a node (region of cells capable of developing new tissue).

Ridge tillage– a management system that plants crops on ridges created by cultivation of the previous year’s crop.

Rosette- cluster of leaves ground close to the ground, generally in a circular pattern.

Scarification- abrasion or scrapes of the seed coat that allows moisture to enter.

Secondary tillage– additional tillage operations that occur after primary tillage to create a finer seedbed often using disks and field cultivators.

Seed rain- seeds naturally released from the mother plant. Seeds may fall directly to the ground, be forcibly ejected a short distance (measured in feet), or released and carried by winds over long distances.
Seedbank (or weed seedbank)— the weed seeds that exist in the plow layer of the soil that could potentially germinate and emerge in the future.

Selection pressure- a phenomena that results in one (or a few weed species) to produce seed and increase in density, while other species are controlled. The phenomena could be herbicides, tillage, biological control organism, etc.

Shank– a metal rod that connects the frame or toolbar to a cultivation tool such as a sweep or shovel. Shanks can be of various shapes including that provide different utility.

Shovel– a V-shaped blade with a raised center (crown) that is used to cultivate the soil.

Site of action- the physical location within a plant cell where the herbicide activity first occurs.

Stale seedbed– Tilling or disturbing the soil several weeks prior to planting the crop to stimulate weed germination and emergence. Emerged weeds are controlled with additional tillage or with other tactics prior to planting.

Stay green- a crop trait that allows the plant to remain green very late into its life cycle, and hinders the plant from drying down.

Stolon- horizontal, aboveground stem capable of producing stems and roots at a node (region of cells capable of developing new tissue).

Summer annual- a plant that germinates from seed in the spring or summer and completes its live cycle before winter.

Sweep– a V-shaped blade that is used to cultivate the soil. They come in different widths and shapes that determine the amount of area tilled and intensity of tillage or soil movement.

Tank-mix- adding more than one herbicide to a spray tank; allows multiple herbicides to be applied simultaneously.
Termination- killing of a plant by any number of methods, including herbicide, tillage or mowing. Often used to refer to killing cover crops.

Trifoliate leaves- plant leaves composed of three leaflets. Soybeans have trifoliate leaves, with the exception of the first set of to develop (see unifoliate leaves).

Tubers- enlarged end of a rhizome or stolon, capable of producing new shoots and roots.

Unifoliate leaves- typically the first set of soybean leaves to develop. These leaves develop across from one another on the soybean stem; but all later developing leaves are trifoliate.

Vegetative stage- the development stage of a plant before it produces any flower structure (including flower buds).

Volatilization- converting a liquid or solid into a vapor or gas stage.

Weed- a plant that is unwanted in a specific setting. Weeds often interfere with human activities and are undesirable.

Weed escapes- weeds that are not killed when they are seedlings and are actively growing late in the vegetative or reproductive stage of the crop.

Weed flush- (synonymous with cohort) all weeds that emerge within a short time period, typically after tillage, planting, or other effect that stimulates weed emergence.

Weed species dynamics– how the agricultural environment changes the abundance of different weed species over time.

Weed species shifts- an agricultural practice or environmental change that allows for new weed species to increase in density, usually as other species decline in density.

White thread stage– the stage after a weed seed germinates and the shoot begins to elongate, but has not yet emerged above the soil surface. In the absence of exposure to sunlight, the shoot appears white and resembles a thread.
Winter annual- a plant that germinates from seed in the late summer or fall and completes its life cycle before the following fall. A plant that is capable of emerging in the fall, surviving the winter, and resuming growth in the spring.