Chapter 9

Integrated Weed Management

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Abstract

Integrated weed management (IWM) strategies are critical for effective long-term management of weeds in the agroecosystem. Knowledge of weed biology is critical for successful long-term IWM, as is integration of multiple methods of weed management. Methods of weed management include preventative, mechanical, cultural, and chemical inputs. Weed managers should develop a management plan that incorporates knowledge of weed biology, consideration of inputs, and effective method evaluation. A good competitive crop will always be the best weed management practice, and a sequence of successful crop rotations are critical for managing weeds in the inland Pacific Northwest (PNW).

Key Points

- An IWM approach depends on knowledge and application of ecological principles, an understanding of plant interference and weed-crop competition, and the appropriate

Research results are coded by agroecological class, defined in the glossary, as follows:

● Annual Crop ▲ Annual Crop-Fallow Transition ■ Grain-Fallow use of preventative, cultural, mechanical, and chemical weed management strategies.

- Herbicides are an effective tool for managing weeds in inland PNW grain production, but they should be used judiciously and in combination with other strategies in order to implement a weed management program that is effective, economical, and prevents the development or spread of herbicide-resistant weed biotypes.
- Examples of IWM strategies for problematic weeds of inland PNW grain production are presented for downy brome, Russian thistle, jointed goatgrass, and Italian ryegrass.
- Anticipated climate change may impact weed management through earlier maturity of weed species, variation in environmental conditions affecting weed-crop competition, shifting ranges of weed species, and indirectly through changes in cultural practices and cropping systems.

Introduction

Effective weed management is achieved by manipulating the crop-weed relationship so that crop growth is maximized while weed growth is minimized or prevented. Weed control tactics are often applied singly without purposeful consideration of the elements of crop production contributing to weed control. IWM is a decision support system for assisting a grower in identification, selection, and use of weed control tactics singly or integrated into a management strategy. An IWM system typically consists of four components: (1) knowledge and application of ecological principles, (2) knowledge of plant interference and crop-weed competition, (3) use of **thresholds**, (4) integration of several weed control techniques, including selective herbicides (Zimdahl 2013).

Weeds are fundamentally different **pests** than insects or diseases. **Integrated pest management** approaches for insects and diseases often include development of host plant resistance or fundamental understanding of beneficial predator-prey relationships. No such efforts have yielded success for weed management in crop production—crop breeders do not specifically focus on improving crop competitiveness with weeds nor have we discovered ways to efficiently capitalize on plant defense mechanisms with weeds, such as allelopathy. Instead, growers have primarily relied on synthetic chemical weed management inputs and tillage to manage weeds on a broad basis, resulting in widespread **herbicide resistance** and soil erosion problems.

IWM systems include not only chemical inputs but also cultural and mechanical inputs (Figure 9-1). An IWM system considers the biology of the weed and crop, informing both short- and long-term management plans based on weed life cycle or seed longevity, for instance. IWM systems also consider the broader impacts of weeds on crop production—an integrated management strategy should include cost-benefit analyses that take into account not only the interests of and impacts on growers, but also on society and the environment (Norris et al. 2003). Such a system is not possible based on the available information and inputs, but rather represents an objective to aspire to. The objective of this chapter is to review the major components of an IWM system for the **inland PNW** small grains production region.

Knowledge and Application of Ecological Principles

Importance of Weed Ecology for Weed Management

Ecology is the study of the interactions between organisms and their environment. Weed ecology gives special emphasis to the adaptive mechanism that enables weeds to survive and prosper under conditions of extreme disturbance, ideally with the goal of identifying specific characteristics or traits targetable for management decisions. The most successful weed management programs are developed on a foundation of understanding weed ecology. Fundamental aspects of weed ecology that lend themselves to management include, but are not limited to, weed response to climate, weed life cycles, weed seed biology, and seed dispersal (Table 9-1).

Knowledge of weed ecology and life cycles enables managers to exploit vulnerable stages of a weed's life cycle and to use targeted control methods during those life stages. For instance, common lambsquarters cannot recover from mowing when they are small, but later in their life cycle they can resprout from the base after a mowing. Additionally, root reserves of

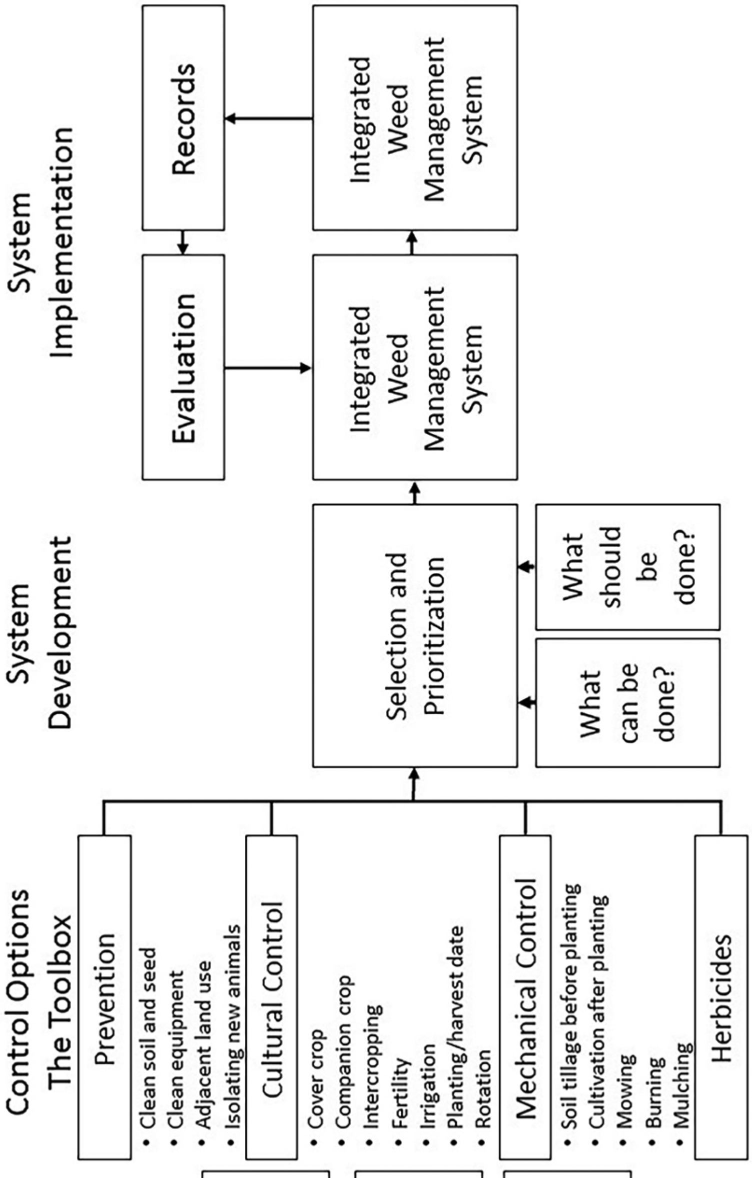

Figure 9-1. A conceptual model for an Integrated Weed Management System.

Table 9-1. Dispersal mechanisms, dormancy type and length, management to induce germination, seed production and seed persistence for common weeds in inland PNW dryland small grain production systems.

Weed	Dispersal mechanism	Dormancy type/length	Management–induced germination	Seed production	Seed persistence	
Grasses						
Downy brome	Humans/ livestock/simple dehiscence/ wind	Physiological/3 months to >1 year	Tillage/fire/ overgrazing	Up to 10,000 seeds per plant	<4 years	
Italian ryegrass	Humans/ livestock/simple dehiscence	Physiological/ 0 to 3 years	No-till	100,000 to 300,000 seeds per plant	Up to 3 years	
Rattail fescue	Humans/simple dehiscence	Physiological/ 0 to 2 years	No-till	0.6 to 11.2 g per plant	Up to 3 years	Ball et al. (2008)
Jointed goatgrass	Humans/ livestock/simple dehiscence	Physiological/ 0 to 1 year	Tillage	Up to 3,000 seeds per plant	Up to 5 years	Donald and Ogg (1991)
Cereal rye	Humans/simple dehiscence	Physiological/ 0 to 1 year	None	Up to 50 per plant	<2 years	

Table 9-1 (continued). Dispersal mechanisms, dormancy type and length, management to induce germination, seed production and seed persistence for common weeds in inland PNW dryland small grain production systems.

Weed	Dispersal mechanism	Dormancy type/length	Management–induced germination	Seed production	Seed persistence	
Broadleaves						
Common lambsquarters	Humans/ livestock/simple dehiscence	Physiological/0 to 3 years	Tillage, soil nitrate	Up to 176,000 seeds per plant	Up to 20 years	Harrison (1990); Bassett and Crompton (1978)
Prickly lettuce	Humans/ livestock/simple dehiscence/ wind	Physiological/0 to 3 years	Tillage/fire/ overgrazing	100 to 200,000 seeds per plant	Up to 2 years	Weaver and Downs (2003)
Russian thistle	Humans/simple dehiscence/ wind	Physiological/0 to 2 years	None	Up to 100,000 seeds per plant	Up to 3 years	Beckie and Francis (2009)
Kochia	Humans/simple dehiscence/ wind	Physiological/0 to 10 years	Tillage, overgrazing	2,000 to 25,000 seeds per plant	Up to 3 years	Friesen et al. (2009)
Redroot pigweed	Humans/ livestock/simple dehiscence/ wind	Physiological/0 to 3 years	Tillage, soil nitrate	200 to 100,000 seeds per plant	Up to 30 years	Costea et al. (2004)
Mayweed chamomile	Human/ livestock/water	Physiological/0 to 2 years	Tillage	5,000 to 17,000 seeds per plant	Up to 11 years	Gealy et al. (1985); Lyon et al. (2017)

perennial weeds can be depleted via multiple, repeated tillage or mowing operations during a season.

Weeds and Climate

Weed seed germination and plant development are strongly dictated by climate. The presence of soil moisture and sufficient diurnal fluctuation of soil temperature stimulate seed germination of many weed species. During vegetative growth, plants use temperature and day length as cues to begin the reproduction cycle. Seasonal variation in climate drives variation in weed management input timing in the same way it drives crop production inputs. Climate variability can be a contributing factor to seasonal successes and failures in weed management. Weed species express a large amount of phenotypic plasticity and are usually adaptable to a wide range of climates. **Adaptation** to climate likely occurs on a local level, including at the field scale.

Weed Life Cycles

Plant life cycles are classified into three types: annuals that reproduce by seed in a single calendar year, biennials that reproduce by seed in more than one calendar year, and perennials that live three or more years and reproduce by seed or perennial survival structures. Knowledge of weed life cycles facilitates identification of the approach and assessment of the commitment required to manage them. Annuals and biennials require fundamentally different approaches than perennial weeds because of their respective life strategies. Perennial weeds typically produce a lower quantity of seed, or sometimes none at all, relying on the perennial survival structures. Annuals, by contrast, reproduce strictly by seed. Seed management approaches can be quite different from perennial propagule management approaches.

Weed Reproduction and Dispersal

Weed species reproduce and disperse by seeds, with the exception of perennial weeds like field bindweed and Canada thistle. Weeds are capable of producing a vast quantity of seed. One of the most prolific seed producer in inland PNW agronomic systems is common lambsquarters, which is capable of producing up to 176,000 seeds per plant (common lambsquarters plants average far less when growing in competition with a crop, though). Grass weeds generally produce less seeds per plant, but often occur in high enough densities to produce very high seed loads per unit area. In agronomic settings where weeds are growing in competition with crops, weed seed production tends to be much lower, but still significant.

In addition to producing large amounts of seed, newly produced weed seed are usually initially dormant. Seed dormancy is essentially seed dispersal through time. Dormant seed, when presented with conditions for germination, do not germinate. The consequence of weed seed dormancy is that a grower is often managing weeds arising from seed set in multiple previous years. There are three primary types of dormancy: physiological, physical, and developmental. Weed seed with physiological dormancy require light to germinate. Physical dormancy is conferred through a hard seed coat that is largely impervious to moisture. Developmental dormancy, most common in grasses, is dormancy conferred when weed seeds are not fully developed when they are shed. Combinations of two or even all three can be found in plants. Managing weed seed with consideration of seed dormancy and seed numbers often involves thoughtful application of tillage to place seed where it cannot germinate, or to stimulate germination. For example, tilling at night in the absence of light nearly stops the germination of weed seed with physiological dormancy. When there is a failure to control weeds and a substantial amount of weed seed is deposited in the soil, inversion tillage could be used to bury the seed to a depth where it cannot successfully emerge. Repeated inversion tillage will bring the seed back to the surface, though. Alternately, tillage or irrigation can be used to stimulate germination prior to planting.

Finally, many weed seeds typically have specialized dispersal mechanisms that enable long-distance movement. Some of our most common weed species are tumbleweeds, where the entire plant is adapted for long distance dispersal via wind. Weed seed can also be transported by humans, particularly as a contaminant in crop seed, hay, and movement of implements, livestock, and other agricultural commodities. Some weed species, like jointed goatgrass and cereal rye, have seed of similar shape and size as wheat, making it very hard to separate the seed of the two species, which facilitates dispersal by growers. Weed seed production, dormancy, and dispersal mechanisms are key factors in the development of IWM strategies for a given weed species.

The Weed Seedbank

The species composition and density of weed seed in soil, called the **weed seedbank**, varies considerably and are tightly linked to past cropping history, seed durability and dormancy. The species found in the weed seedbank varies from field to field and even in areas within fields. Most weed seedbanks are dominated by a few species and these species represent the primary weed pests of the cropping system. A lower fraction of the seedbank—as much as 20%—is composed of species that were formerly dominant, potentially dominant, or simply adapted to the area but not current production practices (Zimdahl 2013). A small fraction of the seedbank consists of very old germinable seeds or newly introduced seeds, with the balance of the seedbank composed of seed deposited in the previous two years. New seeds can enter the seedbank following multiple pathways, but most seed is deposited in the weed seedbank from weeds producing seed within a field. Weeds growing with crops produce far less seed than weeds in open spaces due to crop competition, management inputs, and other factors. Although seed production in most weeds can be reduced by management inputs, seed production will likely remain substantial enough to maintain or increase the seedbank. Seed also enter the seedbank from external sources that can include farm equipment, contaminated crop seed, or long-distance dispersal by wind, animals, and water. Although typically much smaller numbers of seed are introduced from external sources, those sources are the way new species are introduced. Movement of weed seed by combines and other harvest equipment is of particular concern (Currie and Peeper 1988).

The abundance of weed seed in the soil can range widely and is dependent on past success or failure to manage weeds (Zimdahl 2013). Weed seed abundance can range from 300 to 350,000 seeds per square yard (Koch 1969), equating to 1.2 million to 1.4 billion seeds per acre. The abundance of weeds in the weed seedbank in the PNW are similar in size—densities have been reported ranging from ~300 to ~5,000 seeds per square yard in low precipitation zone field sites (Thorne et al. 2007). ■ As aboveground weed productivity increases, the composition of the weed flora and the seedbank changes as well. Mayweed chamomile and Italian ryegrass densities were as high as 28,274 and 77,547 seeds per square yard in fields near Pullman, Washington (Unger et al. 2012). ●

Once in the soil, a host of processes act to reduce the germinable seed bank. Not all of the seeds germinate at once. There is a growing list of seed predators, including earthworms, some carabid beetles and other insects, birds, and small mammals that are known to utilize weed seed as a food source. Seeds are also exposed to the same disease pressure as crop seed, and soil microbial community activity can play a large role in the persistence of certain weeds in the seedbank. Managing for weed seed disease and predator pressure can be difficult, is not well understood, and is an area of active research. Steep declines are observed in seedbank populations when effective integrated management strategies are employed. Unfortunately, even a 95% reduction in the seedbank results in a germination rate that is still a problem to be managed. Furthermore, if there is a single failure to manage a weed cohort in a season, the seedbank is effectively replenished from the resulting seed production.

Interactions between Weeds and Other Crop Pests

Weeds often act as alternate or reservoir hosts for diseases and insects. Management of weeds to facilitate management of diseases and insects is critical for a successful integrated pest management program (Cook et al. 2000). Consideration for the **green bridge** effect and weed-pest relationships are covered in other chapters of this book. In most cases, a good IWM plan, where weeds are effectively managed, will reduce or mitigate weeds as alternate hosts for diseases and insects.

Plant Interference and Crop-Weed Competition

Interference is an alteration of crop growth due to the presence of another plant. Interference is most commonly a negative effect, but it can be a neutral or positive effect in certain situations. Of particular concern to growers is the negative interference called competition.

Competition is where a weed utilizes water, light, or nutrients to the detriment of crop plants. Competition is strongly influenced by crop and weed density, but also by relative proportion and spatial arrangement of the species in the interaction. Density is the number of individuals per unit area, and proportion is the relative ratio or abundance of each species in the interaction. Spatial arrangement is usually quite random for weeds, but somewhat less so for crops. Competition is strongly related to vigor of the species involved and the timing of germination and establishment. Manipulating all of these factors purposefully with conscious knowledge of the biological relationships forms the basis of cultural weed management.

In order to relate the complex interactions associated with competition, weed scientists have devised a series of thresholds that relate the density of weeds or timing of competition to the crop yield loss that results. As weeds increase in density, the proportion of the total biomass production is shifted toward weed biomass. The resulting crop yield loss is quantifiable and can be assigned a monetary value. The basis for the array of thresholds is the law of constant final yield, which states that the biomass production of a given area is critically linked to the resources available, and that a wide range of plant densities (except for very low densities) will result in the same yield of biomass. By understanding and manipulating crop density and reducing or eliminating weed growth, crop biomass is the only biomass produced in a given area.

Thresholds in Weed Management

There are three primary types of thresholds: damage, period, and economic thresholds. Thresholds are expressed in density or weed biomass per unit area—in the inland PNW, biomass is often a stronger predictor of yield loss than density. Damage thresholds, the simplest type of threshold, quantify the weed population when there is a detectable negative crop response. Economic thresholds take damage thresholds and determine the economic damage that equals the cost of a management input. Economic thresholds assist growers in deciding on the return on their management input investment. Period thresholds define a time span during crop production where crops are **susceptible** to yield loss (as indicated in Figure 9-2, a conceptual period threshold for winter wheat).

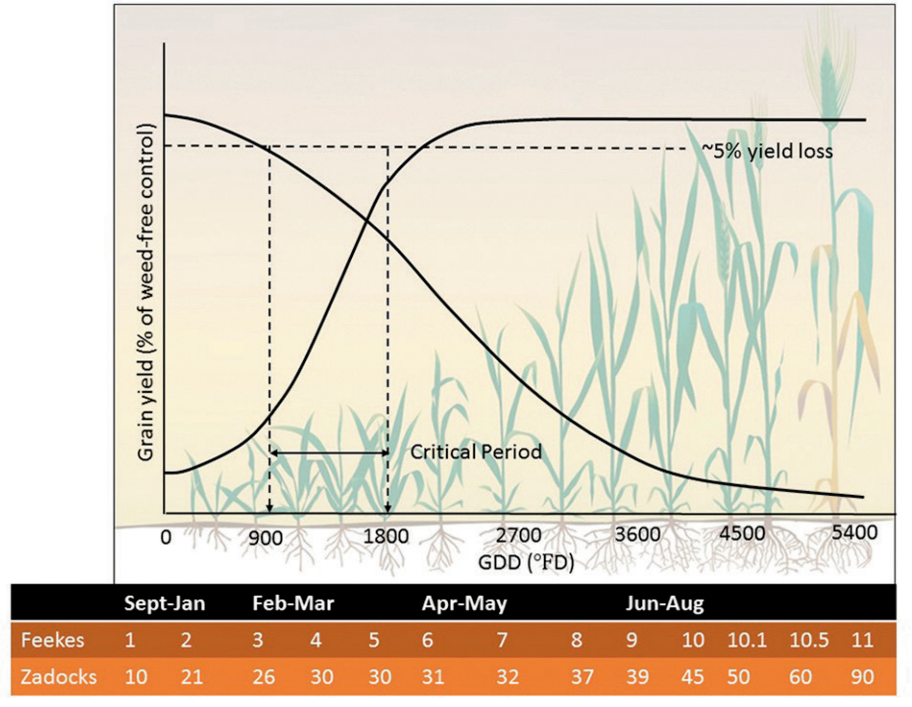

Figure 9-2. The critical period of weed control in winter wheat based on growing degree days, wheat growth stages, or calendar months. Year-to-year variation in climate, and climate change in general, can alter the relationship significantly. The critical period of weed control often occurs early in crop growth and development, and although weeds present in crops after the critical period can cause harvest losses and dockage, they won't reduce yield. The critical period of weed control is based on two components, indicated by the pair of solid black lines: the weed-free period (indicated by an increasing yield the longer the crop is kept weed-free from planting) and the weed infested period (indicated by diminishing yield the longer the crop competes with weeds from planting). (Adapted from Welsh et al. 1999.)

Thresholds can change considerably from year to year even in the same crop as resources and growing conditions vary. Often, damage thresholds can be much less than 1 weed per square yard, and in any case, growers usually always apply a herbicide at some point during the growing season (99% of inland PNW wheat crops are treated with a herbicide during the growing season). Consequently, thresholds are seldom employed to make herbicide decisions in the inland PNW in the same way that thresholds are used to manage insect pests (see Chapter 11: Insect Management Strategies). Unlike insects and diseases, weeds always exceed thresholds stimulating treatment.

Weed Management Inputs

Preventative Weed Management Components of IWM

Preventative weed management refers to all activities that will reduce or eliminate the opportunity for new species to enter an area or for weeds present in an area to persist. Examples of preventative weed management include using clean weed seed-free crop seed for planting, cleaning harvesters and tillage equipment frequently and particularly between fields, and preventing the reproduction of weeds. The most recent development in preventative weed management is harvest weed seed control. A grower invention, harvest weed seed control involves managing seed that has not shattered out of the seed head. A wide range of approaches have been developed, largely in Australia, where early efforts focused on windrowing and burning chaff. Chaff carts of several different types were also developed, and the chaff was then burned. The most recent development is a chaff management system paired with a hammer mill that pulverizes the weed seed (Harrington and Powles 2012). The management of weed seed is an important yet unrealized opportunity for IWM systems in the inland PNW.

Cultural Weed Management Components of IWM

Crop rotation

Crop rotation is a critical component of IWM systems. Weeds typically associate with certain crops—wild oat or jointed goatgrass in winter or spring wheat, for example. Weeds can also adapt to management philosophies, like rattail fescue in **no-till** systems. When the same crop is produced repeatedly in the same area, weeds that associate with that crop typically increase, as the same environmental and cultural conditions that facilitate crop growth facilitate weed success. Over several rotations, the population of adapted weeds can become large.

Intensive crop rotation maximizes opportunities for varying competitive attributes among crop species (e.g., growth form and rate, life cycle length, water and nutrient use efficiency, and nitrogen fixation) (Buhler 2002), reducing the ability for weed species to become abundant. A diverse cropping system inherently includes varying seeding dates, crop life cycle, herbicide modes of action, herbicide application timing (pre-plant, postemergence, pre-harvest, or post-harvest), crop residues, and soil disturbance, and it provides a means of managing weeds by reducing weed densities and reliance on herbicides (Derksen et al. 2002). Extending rotations to 4 years or more improves suppression of most common weeds (Ogg and Seefeldt 1999; Tautges et al. 2016), particularly if rotation includes winter and spring varieties of both cereal and non-cereal crops (Blackshaw 1994; Derksen et al. 2002; Moyer et al. 1994). Different crops compete differently with weeds: barley, oats, and triticale are the most competitive, wheat and canola are marginally less competitive (a spring hard red wheat is the least competitive wheat), and pulses are among the least competitive crops. The more competitive the crop, the less dependent weed management is on other inputs, including herbicides.

Rotational flexibility is strongly influenced by climate and soil, and the climate in the PNW limits rotational opportunities to just a few crops (see Chapter 5: Rotational Diversification and Intensification). In the Grain-Fallow **agroecological class** (AEC) (a large area of central Washington and adjacent north central Oregon), climate (principally annual precipitation) limits rotation to primarily a winter wheat-summer fallow sequence where the summer **fallow** functions to facilitate weed management inputs and store a portion of the winter precipitation (Schillinger and Papendick 2008). ■ IWM approaches in grain-fallow rotations are in many ways similar to a more conventional two year rotation. In areas of the inland PNW with more precipitation, more intensive and complex rotations are practiced. Above ~15 inches of precipitation, a winter wheat-spring cereal or spring oilseed-summer fallow rotation is typical (Annual Crop-Fallow Transition AEC) ▲, and above ~18 inches of precipitation, crops are grown every year (Annual Crop AEC) ● and summer fallow is replaced by a spring pulse or spring oilseed rotation. As rotations are intensified and diversified, IWM systems become more complex and more effective.

Increasing in-season crop competitiveness

Plant characteristics that generally increase crop competitiveness with weeds during early stages of crop growth and development include rapid germination, root and early vegetative development and vigor, rapid canopy closure, increased leaf area index (unit leaf area per unit ground area), leaf duration, crop canopy height, and allelopathic properties (Buhler 2002; Callaway 1992; Pester et al. 1999). Rapid shading of the ground and crop resource capture increases early season crop competitiveness. Facilitating rapid canopy coverage of the ground reduces weed seed germination. Yield loss declines the longer weeds are kept from establishing and competing with the crop for resources. Increasing the competiveness of the crop is among the least expensive IWM inputs. Inputs that increase competitiveness are usually associated with "good farming" and are typically activities that would occur in the course of crop production. Thinking about how those very simple decisions, like choice of cultivar, seeding rate, and placement of fertility inputs, affect crop competitiveness and weed management are integral to an IWM system.

Competitive cultivars

The choice of crop cultivar can affect the competiveness of the crop. Cultivars often vary in early season vigor, leaf growth and size, and crop height-even how the leaves of wheat nod can affect competiveness. Plant breeders note such information but it is not widely reported, so growers are encouraged to explore variety trials not only for highest yield but for growth and development throughout the season when selecting crop cultivars for competitiveness. Often the highest yielding varieties, where the **harvest index** has been significantly shifted toward seed production, are not the most competitive. A competitive cultivar is typically combined with other cultural practices to encourage rapid crop emergence and canopy cover, ultimately resulting in increased resource capture by crop plants over weeds (Andrew et al. 2015; Harker et al. 2011). Sacrificing some yield potential by choosing a cultivar with a lower harvest index may result in greater yields because of less weed pressure over time.

Seeding rate

Most growers are familiar with the economically optimal population for crop production. Essentially, for a given piece of ground there is an ideal crop plant population that results in the greatest yield for the minimum investment in seed. Plant more seed above that, and a grower incurs greater expense in seed for no increased yield return. Plant below the economically optimal population, and yield declines (Schillinger 2005). The economically optimal crop population is usually lower than the most competitive population, often by 30 to 100%. Although seeding rate is usually optimized for wheat, pulse seeding rates are often too low for generating competition with weeds (Manuchehri 2012). Planting more seed and growing more plants per unit area reduces the space for weeds to establish, and intensifies the competition for resources not only between crops and weeds, but also among crop plants. Seed rate and crop population are among the most inexpensive ways to modify the competitiveness of crops with weeds.

Row spacing

Like plant population, optimizing row spacing functions to increase crop competitiveness by facilitating rapid canopy development. Row spacing is harder to manipulate as growers seldom are interested in purchasing multiple seed drills or planters to utilize different row spacing. Row spacing is set when the seed drill or planter is set up, usually based on experience or local practice, and all crops are planted to that row spacing. In the Grain-Fallow AEC, row spacing is wider than 15 inches as a moisture conservation tool. ■ In general, row spacing tends to decline as yearly precipitation increases, and the Annual Crop AEC in the inland PNW are planted to 7-inch rows or less. ●

For wheat, 7-inch row spacing in the high precipitation zone is ideal. There is a growing body of evidence that 7-inch rows are too wide for pulse production. In work in Australia, lentil yields were optimized and competition maximized using 3.5 inch row spacing. Dry pea would likely also benefit from planting in row spacing less than 7 inches (Borger et al. 2016).

Fertilization

Timing and location of fertilizer applications maximize nutrient availability to crop plants and reduce nutrient availability to weeds, improving the competitiveness of the crop (Buhler 2002). Banding fertilizer is the typical method used at the time of planting. Winter wheat yields and nitrogen uptake increase when fertilizer is banded 2 inches below seed; weed biomass and nitrogen uptake decrease under banded compared to broadcast applications of nitrogen (Cochran et al. 1990; Reinertsen et al. 1984; Veseth 1985). An in-depth discussion of fertilizer placement for crop production is included in Chapter 6: Soil Fertility Management.

Varying seeding dates

Timing of inputs primarily refers to delaying planting dates to manage weeds that germinate and emerge in the fall or spring. Delaying the planting date allows an application of tillage or herbicides to control weeds that emerge before planting the crop. Varying when many of the typical inputs occur can have a profound impact on weeds that germinate and emerge in a single flush of seedlings, but is less effective for managing weeds that germinate and emerge in multiple flushes. The Mediterranean climate in the inland PNW also limits the utility of delaying the timing of planting for weed management inputs, as a delay in planting usually results in yield loss.

Mechanical Weed Management Components of IWM

Mechanical weed management includes the familiar tillage, but also includes inputs like flooding and applications of heat. Stubble burning is a practice that was once widely applied in both wheat and grass seed production in the PNW. Burning stubble was usually applied as a stubble management input, but had the positive effect of significantly reducing the number of viable seeds. Effectiveness was related to the duration and intensity of the burn, but reductions in seed deposition and viability could be significant. Jointed goatgrass seed numbers were reduced 43% to 64% and reduced seed viability by 95% to 100% (Young et al. 1990; Young et al. 2010). Fire is widely employed in Australia, where growers windrow chaff and then burn it to destroy weed seed.

Tillage or cultivation of the soil is among the oldest forms of weed management. In addition to weed management, cultivation is an important input for seedbed preparation, improving soil physical conditions, precipitation **infiltration**, and incorporation of amendments like fertilizers or herbicides (Radosevich et al. 2007). Cultivation manages weeds by ripping, tearing, or burying them. Small weeds are more susceptible than large weeds, and annuals are usually more easily managed by cultivation than perennial weeds. Weather conditions can influence the outcome of a tillage input—warm, dry weather is preferable to dry the weeds out after cultivation. Tillage is classified into two types: primary and secondary.

Primary tillage is used to prepare the soil for planting. The equipment used in primary tillage can vary widely from very shallow tillage or deep tillage to break a plow pan. Primary tillage implements include the moldboard, disk, chisel, or subsoiler. When used properly, moldboard and disk plows can reposition weed seed on the surface of the soil to the depth of the tilled soil. Secondary tillage is used primarily for weed control, and as a consequence, timing of secondary tillage can vary widely. Secondary tillage equipment seldom disturbs more than the surface of the soil, as deeper tillage would damage crop roots. Tools for secondary tillage include different types of harrows, shovels, sweeps, chisels, rotary hoes, and rodweeders.

Weed control by cultivation is achieved by burying seedlings and small annual weeds with the soil thrown over them through the action of the tillage tools and uprooting them, or severing their roots, resulting in death by desiccation. Care must be taken in the secondary tillage operation so the roots or aboveground parts of the crop plants are not injured. Cultivation too late in the season may injure the root system and make the crop more susceptible to drought. Finally, cultivation may bring up weed seed in the soil profile and place them in a zone conducive to germination.

Secondary tillage has some advantages. In particular, there is a wide selection of implements, and large areas can be economically weeded. The disadvantage of machine tillage is that it does not control weeds growing in the seed row—a problem that may be solved by robotics. Weeds in crops planted in wide rows can be controlled reasonably well, but weeds within crop drill rows usually require hand hoeing or the use of specialized equipment. Depending on how aggressive the secondary tillage, it can control many small annual weeds, but does not work well on perennial weed species. In practice, the variable topography and recommended soil conservation practices (see Chapter 3: Conservation Tillage Systems) preclude the use of in-crop cultivation for weeding in the inland PNW dryland grain production areas.

Chemical Weed Management Components of IWM

Herbicides are sometimes erroneously perceived as the only solution to managing weeds, leading to the idea that weed management is a simple process. Although herbicides are a critical component for a successful IWM system, there are many factors that contribute to successful weed management, and some successful IWM systems do not use herbicides. Often, the element offering the most visible and striking contribution to weed control is the herbicide component of the system. However, when discussing chemical weed management, it is important to remember that many other factors contribute to weed management, including the integration of preventative, cultural, and mechanical inputs that have been previously discussed.

Herbicide selection should not be a decision made in haste. Herbicide selection should be part of planning for the entire crop production process. A major difficulty in selecting herbicides is the focus on trade names over active ingredient names. The proliferation of trade names—the commercial identifier or trademark designation—causes confusion because a single active ingredient can be sold under a variety of different trade names. Roundup, for instance, is a ubiquitous trade name, but the common name (or active ingredient) is glyphosate. The active ingredient is what is responsible for phytotoxicity in a herbicide formulation. While trade names can change, the active ingredient in a herbicide does not change. Many products are available that contain one or more of the same active ingredients for use in wheat. As a result, knowing the common name for a herbicide provides a basis for assessing products and finding the most cost-effective source of a herbicidal active ingredient.

Herbicides are important inventions with significant positive and negative attributes. First and foremost, herbicides facilitate the management of weeds in the drill row where mechanical inputs fail to reach. Some are selective and, when used appropriately, do not harm the crop or other desirable organisms, as crops are **herbicide tolerant**. Herbicides have facilitated the adoption of minimum or no-till systems on a regional and national basis. They reduce time and labor and facilitate early planting by allowing growers to manage weeds when tillage cannot be performed because of soil moisture. Herbicides have dramatically increased the area a single person is able to farm—they are highly efficient labor-saving tools. Herbicides have negative attributes as well, including the potential to injure the crops in which they are used and the potential for off-target injury due to movement away from the site of application. Herbicide use can restrict rotational crops, often significantly. Herbicides have contaminated ground and surface water in areas of the US. Residues of herbicides can remain in and on the crops in which they are used. The large majority of pesticides used in the US are herbicides, and it is testimony to their safety and efficacy that the vast majority of herbicide applications are applied safely and effectively.

Herbicides are used primarily as broadcast applications in the inland PNW. They are usually applied preplant (before the crop is planted), preemergence (after the crop is planted, but before emergence), or postemergence (after crop and weed emergence). Spot treatments are also common. Less commonly used are band applications (applied over the crop row only) or directed applications (applied around the base of the crop, where the crop has a woody stem). Postemergence herbicides are applied with surfactants, spray additives that facilitate transport across the cuticle of weeds.

Herbicides are classified by their mode of action. Mode of action refers to the way a herbicide affects a plant. Inland PNW crop protection systems rely on a very narrow subset of the available herbicide modes of action: the growth regulators, the amino acid synthesis inhibitors, the fatty acid synthesis inhibitors, the photosystem inhibitors, the PROTOX inhibitors, and the seedling growth inhibitors. Knowledge of herbicide modes of action is useful for managing the risk of developing herbicide resistance (see Table 9-2 to assess likelihood of herbicide resistance development on a per species basis). Managing herbicide resistance is critically important, as no new herbicide modes of action have been discovered since the early 1990s.

Herbicide resistance testing, and understanding mechanisms of resistance to herbicides, will be critical to future weed managers and IWM systems. Herbicides are currently applied to entire fields with little knowledge of the status of resistance within the fields. Instead, field managers and growers

Table 9-2. An assessment matrix for likelihood of herbicide resistance development. To self-assess, it is critical to know how many herbicide active ingredients in a mixture have activity on the weed being managed, and ultimately how many modes of action are employed for the control of a single species.

Management Option	Low	Moderate	High
Herbicide mix or rotation in cropping system	>2 modes of action	2 modes of action	1 mode of action
Weed control in cropping system	Cultural, mechanical, and chemical	Cultural and chemical	Chemical alone
Use of same mode of action per season	Once	More than once	Many times
Cropping system	Full rotation	Limited rotation	No rotation
Resistance status to mode of action	Unknown	Limited	Common
Weed infestation	Low	Moderate	High
Control in last 3 years	Good	Declining	Poor

Adapted from Moss 1998.

select herbicides based on cost and on broadly successful treatments. In the future, managers will likely be testing for resistance broadly and using a range of old and new herbicides based on knowledge of the response of different populations within fields. Employing generic inexpensive herbicides where they are effective, and doing so with knowledge of the resistance status of the weed being managed, has the potential for reducing the economic cost of managing weeds.

Societal and Environmental Considerations

Public perceptions and expectations often influence the management tactics that are available to growers of a given commodity. For example, in the inland PNW, transgenic glyphosate-resistant wheat was discarded as a management tactic because of the inability to manage volunteer transgenic wheat in rotation. There were also concerns on the part of the primary overseas markets, who indicated that they would not accept transgenic wheat. Public policy at multiple levels can also be influenced by public perceptions and expectations—sometimes such influence is driven by emotion rather than science. Such influence can limit tactics available for use in IWM systems. Educating the public on the scientific basis of IWM is critical for enabling the greatest possible suite of inputs and limiting misdirected public policy (Norris et al. 2003).

Pesticide use comes with risk. Herbicides are strictly regulated, and the herbicide label sets forth directions for use that ensure that residues that enter the food system are only present at, or lower than, EPA-mandated levels. Although chronic long-term exposure to traces of correctly applied pesticides can be of concern, the risk associated with most exposures is viewed as very low (Norris et al. 2003). Food-borne diseases, malnutrition, non-pesticide related environmental contaminants, and naturally occurring toxicants are all considered more important than pesticide residues when making a risk versus benefit analysis. Nevertheless, public perception of pesticides continues to be negative. It is critical that those that use pesticides do so according to label directions.

Environmental issues in the inland PNW related to IWM are considerable. The practice of tillage in the inland PNW directly contributes to the highest rates of erosion in the US. As a result of concerns over airborne dust, PM10 standards (particulate matter standards that apply to particles 10 micrometers or less) were developed that regulate the reduction of tillage, increasing reliance on herbicides. Herbicide drift is a major concern in the inland PNW. As orchard and vineyard acreage increase, limits on the application of volatile formulations of herbicides are increasing. Certain volatile formulations of 2,4-D are currently prohibited in the state, and there are very specific limitations on when less volatile formulations can be applied. The burning of agricultural fields, a weed and crop residue management practice, has been very tightly regulated, limiting the length of grass seed field productivity. When a weed management tactic is lost, it often places pressure on alternative tactics, or there is a reduction in productivity until effective alternatives are found. Ultimately, social concerns have had, and will continue to have, a profound influence on IWM systems in the inland PNW.

Developing an IWM System

A systematic approach to developing a weed management plan should be followed to implement an IWM system (Figure 9-1). Steps to developing and executing a weed management plan could include (1) problem diagnosis, (2) program selection, (3) program execution, and (4) method evaluation (Ross and Lembi 1999).

Problem Diagnosis

The first step in designing an IWM system is a systematic review of both the problem weeds to manage and the environmental conditions they are to be managed in. Although not exhaustive, the list should capture most of the important factors for consideration. A practitioner is encouraged to identify additional components based on local knowledge.

Weed identification

Identification of the species present in the area to be managed is critical for success. As noted previously, knowledge of the biology and ecology of the weed species facilitates biologically based management strategies.

Weed abundance

The abundance and economic importance of each species in the field, ideally based on economic thresholds, should be determined. Identification of both important species with high abundance as well as those that are in small areas or in low abundance should be performed. Scouting in-season and in the fall is a critical part of the process as weeds present at harvest will likely produce seed and thus be problems for at least the following season (usually for at least 2 years, and sometimes more than 10 years). Scouting also facilitates an early detection rapid response approach. Depending on the weed complex and the production system, management options may be very limited. Fields usually contain a mixture of broadleaf and grass weeds. Interestingly, an effective IWM system is often indicated by low populations of a diversity of weed species.

New weeds

Weeds not present in an area or field before must be recognized and managed. Small patches of a new species is indicative of an invasion process just beginning. A preventive program is critical to managing weed species that could become serious weed problems, such as Italian ryegrass, downy brome, jointed goatgrass, prickly lettuce, mayweed chamomile, field bindweed, Russian thistle, or common lambsquarters, and will be an excellent return on the investment in time and energy if these weeds are prevented from invading a non-infested area. Growers cannot assume that these weeds will be easily and economically controlled with modern herbicides. For example, numerous biotypes of Italian ryegrass **resistant** to both ALS (Group 2/B) and ACCase (Group 1/A) herbicides occur in the high precipitation zone. Widespread resistance to the Group 2/B herbicides also occurs in downy brome. Mechanical and cultural methods have to be employed to manage weeds resistant to available herbicides.

Soil

Understanding soil chemistry is essential when working with soil-active herbicides. Additionally, certain weeds associate with specific soil environments or soil types—some weeds can tolerate acidic soil conditions, for example. Soil texture (% sand, silt, and clay) affects soil **water holding capacity** and, as a consequence, the rate of herbicide and water movement. Soil conditions while planting, tilling, and applying herbicides can be critical for success of the input. Surface moisture, plant residue, and soil surface roughness all affect the outcome of a soil-applied herbicide. Different soil types within the same field can result in reduced selectivity in areas of the field where the binding of the herbicide to soil is weak. Plants under water stress do not respond to herbicides, and functional soil drainage in wet areas would be considered an input for weed management.

Texture and organic matter

Consider the soil texture and organic matter. Both can impact the safe use of soil-applied herbicides, particularly in large fields with variable soil found in the PNW. Eliminate those choices that do not fit the soil type or types prevalent in a given field. Guidance on use of inputs based on texture and organic matter are found on herbicide labels or in Extension publications.

Soil pH

The soil **pH** determines the chemical charge of some herbicides, and each of those herbicides responds to pH in a different way. Soil pH strongly affects the amount of dissolved herbicide in the soil water fraction. In general, herbicides sensitive to soil pH vary in their solubility, and pH can affect the persistence, or lack of persistence, of the herbicide in the environment. Although too complex to fully address here, a PNW publication is available (Raeder et al. 2015).

Erosion potential

The inland PNW has some of the highest soil erosion rates in the world, so systems for maintaining crop residues in place are common. However, maintaining crop residues often precludes the use of machine tillage inputs, with a few exceptions. Herbicide incorporation by tillage cannot be used in no-till production. No-till or minimum tillage systems increase dependence on herbicides. Eliminating soil disturbance often changes the species of weeds to be managed.

Crop rotation

The previous and planned future crop rotations are critical to consider. Integral to any crop rotation is the herbicide use in each rotation, as certain herbicides can limit rotational flexibility. Canola is an excellent example of a crop that is highly sensitive to certain herbicides. Crop rotation is essential for IWM, and growers are encouraged to use methods that allow them to be flexible.

Program Selection

Selection of inputs should be based on effectiveness of weed control and cost. Rather than relying on a single input like a herbicide, the goal is to purposely choose and apply a variety of components (Ross and Lembi 1999). Consider the following when selecting elements of an IWM program.

Economic return

The cost of the various inputs should be considered in the context of economic return. Using economic thresholds can help assess the return on investment of various IWM system components.

Management system

The input needs to be compatible with the current system, and the manager needs to have the capability to execute the input.

Equipment

Equipment needs to be available and of a size that makes the operation feasible in a limited time period.

Custom services

Both field managers and consultants need to be reliable.

Time

Can the input be effectively applied over the required area in the window of opportunity available?

Operational capability

Can staff accomplish the operation?

Crop and management system

Is the input compatible with the long term rotational plan?

Identification of the problem weeds to be managed the following year facilitates a narrowing of management options. For example, the list of prospective herbicides for a crop could be narrowed on the basis of available herbicides that actually have activity on the weeds present in the field. Charts of herbicide efficacy are usually available (see the PNW Weed Handbook or the WSU Small Grains website in Additional Resources for such charts). Create a list of active ingredients that best fit the weeds to be managed, and then identify the herbicide products that contain those active ingredients. The herbicides should be selected on a field-by-field basis—not the entire farm (in the future it will be on a subfield basis). The use of specific herbicide programs for individual fields may not be practical, and growers usually group fields with similar weed problems. However, given the size of farms in the PNW, the blanket application of a few products to an entire farm is likely wasteful. Modern farm management software should allow growers to quickly and easily target problem fields with more expensive herbicides and manage less weedy areas with less expensive but equally effective herbicides.

Value of early season programs

Early season programs are critical for spring-sown crops, as weeds germinate and emerge at nearly the same time as the crops. Management inputs should be planned to keep spring-sown crops weed free for the first weeks of growth. Pulses often require a weed-free period of 6 weeks or longer. Ideally, the plan should include alternatives in case management inputs fail in the first few weeks of crop growth.

Rotation of herbicide modes and sites of action

Use herbicides with different modes and sites of action for weed management. There is a growing body of evidence that when using two herbicides with different modes of action that have activity on the same weed, applying them simultaneously (in the same application) is a more proactive resistance management strategy than applying them sequentially (rotating between modes of action). Although there are not enough options to effect this strategy for grass weed control, it is easily accomplished for broadleaf weed control.

Herbicide resistance is a very complex phenomenon, and rotation of herbicide families or modes of action is an oversimplified solution. Many herbicides and modes and sites of action are used on more than one crop. For example, growing conventional canola and a pulse in rotation is not an effective herbicide rotation because the same herbicide mode of action is employed to manage grass weeds. Using two herbicide modes of action to control each weed species is the ideal approach to manage resistance, but such an approach is not possible in some cases. Routine herbicide resistance testing is part of the IWM approach for wheat producers in Europe and Australia and should be considered essential for PNW growers, too. Testing for resistance allows growers to choose herbicides with the knowledge that they will be effective.

Herbicide resistance

Managing for herbicide resistance is often only addressed after resistance develops. Resistance to herbicides is a symptom of a flawed IWM system. The solution is often a careful evaluation of the system and deployment of additional control tactics (e.g., doing what should have been done prior to the development of resistance). The list of management inputs to choose from does not change once herbicide resistance occurs. Therefore, growers are encouraged to be proactive. Develop and execute an IWM plan before resistance occurs. A herbicide-resistant weed is a much higher priority for management.

Program Execution

Execution is a critical step in an IWM system. Three factors are essential: (1) operations must be completed in a timely fashion, (2) the right equipment must be used, and (3) equipment must be correctly operated (Ross and Lembi 1999).

Appropriate follow-up

Monitoring the outcome of weed management inputs should be planned as part of the system. By carefully recording and observing the outcome of each management input, growers can assess whether to continue the management practice or to alter or forgo it altogether.

Weed managers are encouraged to be realistic and to recognize that not all the weeds need to or can be controlled. By integrating multiple management inputs into a complex program, weed management can be achieved successfully and for multiple seasons. Managers are often overly optimistic and rely on a few inputs over a long period of time. Products and technologies are often over-promoted, and managers always seem to be interested in the one input that will take care of everything. A sensible, rational, realistic long-term IWM plan is the most effective strategy for managing weeds.

Method Evaluation

A careful assessment of currently available management inputs is the final step in devising an IWM plan. There are a wide range of resources available, including Extension material based on field trials. Weed scientists, agricultural Extension specialists, agricultural consultants, and industry representatives are excellent sources of information on new or novel management inputs. The inputs should be evaluated for specific criteria (Ross and Lembi 1999).

Past weed management systems and results

A careful evaluation of past experience must be conducted every year. Management inputs that were effective should be retained, while those that were not effective should be reconsidered. Careful assessment of weed populations at the field level should be mapped, and the mapped populations monitored. Shifts in weed species composition are often observed when a change in management tactics is applied. Often it takes 10 years or more for the shift to occur.

Effectiveness

Consider the effectiveness on each weed species present.

Consistency

How consistent is the outcome? Variation in the outcome of a system is an indication that the system is vulnerable to failure. Sometimes, evidence of consistency is as subtle as choosing to use a higher rate of a herbicide because of a sense of failure from the previous year or application.

Fit within the individual system

Will the management input fit into the current system? Incompatibility comes in many forms. Tillage is, of course, incompatible with no-till systems. Pesticide compatibility can also be a concern, particularly when systems use a single pass to apply multiple pesticides. Although the pesticides may be compatible in mixture, the complexity of such mixtures can complicate troubleshooting when there is problem, and there is increased risk of injury and reduced weed control.

Flexibility

If the timing of an input is critical for success, consider that weather in the inland PNW is quite variable, and the window of opportunity for application of a management tactic is often only a day. Can the input be applied in such a tight window based on climate and crop growth and development?

IWM of Selected Problematic Weeds of the inland PNW

Downy Brome ▲ ■

Downy brome (*Bromus tectorum*) is a winter annual and **facultative** spring annual grass that develops early in the season, usually flowering in April and May. Downy brome reaches seed maturity at an average of 1,000 **growing degree days** (a measure of thermal time) in the inland PNW (Ball et al. 2004; Lawrence and Burke 2015). No-till spring cropping helps control downy brome because downy brome plants that establish during the fall and winter can be controlled with a herbicide or tillage before spring seeding (Thorne et al. 2007). Average downy brome seed persistence is 2 to 3 years (Thorne et al. 2007), though some seeds can persist longer. Dormancy is thought to be more complex than previously realized, and there is a wide range of dormancy periods (Hauvermale et al. 2016). Downy brome seed deposited in the soil seedbank can be reduced when light tillage is used in combination with fall or spring herbicide applications (Yenish et al. 1998; Young et al. 2014), but such an approach seldom completely solves the problem.

Cultural management of downy brome usually requires manipulation of crop rotation, tillage, and nutrient management. Growers should avoid excessively early seeding because it can promote yield-reducing disease and insect pests in grain-fallow systems (including barley yellow dwarf, wheat streak mosaic, dryland foot rot, Cephalosporium stripe, strawbreaker foot rot, stripe rust, Russian wheat aphid, greenbug aphid, and others, see Chapter 10: Disease Management for Wheat and Barley and Chapter 11: Insect Management Strategies). If rains occur just before the planned planting date, delay seeding, wait for downy brome to emerge, and apply a non-selective herbicide or tillage before seeding. However, avoid seeding later than the optimal planting date to avoid yield loss due to other climatic and growing season conditions (Yenish et al. 1998).

General IWM principles should be applied: plant competitive, vigorous varieties; avoid using excessive nitrogen; top dress only when needed; and deep band nitrogen to limit availability to downy brome. Crop rotation to spring crops or fall-seeded broadleaf crops, such as winter canola or winter pea, facilitates use of in-crop grass herbicides in order to minimize downy brome seed production (Yenish et al. 1998). Alternative crop/fallow rotations for downy brome management include winter wheat-fallow-spring wheat, winter canola-fallow, or other permutations of cropping sequence that facilitates the use of effective spring inputs. Rotating out of winter cereals for a minimum of 3 years is key to managing infestations (Yenish et al. 1998).

Use a combine chaff spreader to distribute seed, and then harrow or perform other light tillage (tine harrows or skew treaders) soon after harvest to increase seed-soil contact and subsequent germination when fall precipitation occurs. Wheat yield loss is most severe when downy brome germinates within 21 days of wheat emergence; beyond this point, only extremely high-density downy brome reduces wheat yield (Rydrych 1974; Blackshaw 1993). When downy brome emerges within 14 days after wheat emergence, downy brome densities of 24 plants per yard and 65 plants per yard can reduce wheat yield by 10% and 20%, respectively (Stahlman and Miller 1990).

Integrated management of downy brome using herbicides is very challenging due to the lack of options. Herbicides for downy brome management are limited to the Group 2/B herbicides: pyroxsulam, sulfosulfuron, propoxycarbazone, mesosulfuron, chlorsulfuron, and imazamox, which form the basis for herbicidal control of downy brome. Interestingly, all Group 2/B herbicide products are labeled for control in fall applications, but only spring suppression. Most growers apply these herbicides postemergence in the spring to control both fall- and spring-emerging downy brome, and to ensure that replanting can be accomplished if needed. Suppression is the most common outcome of such applications.

Applying a downy brome growing degree days model to climate change model projections for the inland PNW indicate that downy brome may reach seed maturity between 15 to 25 days earlier by mid-century (2031–2060) (Lawrence and Burke 2015). Late flowering biotypes of downy brome are predominantly located in the Palouse region (eastern Washington). Early flowering biotypes dominate the central Washington wheat region. Eastern Washington (late-flowering biotype region) is projected to undergo the greatest amount of change in growing degree day accumulation. Early flowering biotypes may spread to the east due to the changes in growing degree day accumulation, as they are better adapted to warmer springs and milder winters. Several early flowering biotypes have herbicide resistance to ALS-inhibiting herbicides (Lawrence and Burke 2015). Earlier downy brome development and greater spring precipitation may limit the opportunity for in-field spring treatment of downy brome. Herbicide effectiveness may also decline with the spread of resistant biotypes (Lawrence and Burke 2015).

Russian Thistle ▲ ■

Russian thistle (*Salsola tragus*) is a summer annual broadleaf weed. Russian thistle is most troublesome in spring crops but can be a problem in winter wheat and during fallow periods (Young 1998; Schillinger and Young 2000; Thorne et al. 2007). Preventive management of Russian thistle is important, and includes controlling populations along borders and non-cropped areas because of its "tumbleweed capability" of very long distance dispersal (Young et al. 1995). Russian thistle germinates in the early spring through late summer, and flowers all summer and into fall until a killing frost (Young et al. 1995). Matured seed requires a fall after-ripening period. After an after-ripening period, Russian thistle seed can germinate under a wide range of conditions in the spring, even at relatively low temperatures (37°F to 42°F) (Young and Evans 1972; Thorne et al. 2007; Young and Thorne 2004). Russian thistle can be controlled within a few years by preventing seed production (Thorne et al. 2007), assuming no new introductions occur. The majority of seed viability declines within 2 years—management should focus on preventing seed production or new introductions (Young et al. 1995). A significant amount of flowering occurs after harvest, and Russian thistle can regrow after being cut by a combine. Russian thistle exhibits an indeterminate growth habit, and will continue to grow and set seed until temperatures drop below 25°F.

Russian thistle has high **water use efficiency**. If left to grow post-harvest, Russian thistle can reduce soil water storage for the next crop in rotation (Young et al. 1995) and usually causes the greatest damage under drought conditions, in thin crop stands, or if the crop is planted late (Young et al. 1995). One Russian thistle plant can use up to 18.5 gallons of soil water while growing in a spring wheat crop. Post-harvest growth uses an additional 26.5 gallons and accumulates significant biomass until killing frost occurs late October (Schillinger and Young, 2000).

In-crop management is usually accomplished with non-selective and selective herbicides, depending on timing. Both pre-harvest and post-harvest control is achieved with a non-selective herbicide. During fallow, control is achieved with herbicides or with tillage, usually with a rodweeder or an undercutter sweep (usually operated to a depth of 4 inches, which is more effective than 2 inches). Timely application of tillage is essential, as larger Russian thistle can survive rodweeding.

Management in the fallow year usually includes spring non-inversion tillage with wide-blade sweeps followed by 2 to 3 secondary treatments with a rodweeder to help retain surface residue (Schillinger and Young 2000). For spring crops, spring wheat should be planted early and in narrow row spacing (6 to 9 inches) to increase crop competitiveness. Spring wheat cultivars with rapid and prostrate early growth increase spring cropping for controlling Russian thistle (Schillinger and Young 2000). Post-harvest treatment using an undercutter V-sweep can consistently kill Russian thistle, eliminate seed production, retain more soil water in the fall post-harvest, and produce greater spring wheat yields in the following year compared to using only a post-harvest treatment of paraquat + diuron, alone. Paraquat treatment allowed greater soil water extraction post-harvest and allowed production of an average of 370 seeds per square yard from lower branches where herbicide did not penetrate (Schillinger 2007).

Russian thistle may not be as great a problem in no-till spring crop rotations as it is in tillage-based spring crops. Summer annual broadleaf weeds are usually most successful in systems that include intensive tillage (Derksen 1993; Thorne et al. 2007).

Sensor-based (e.g., a Weed Seeker by Patchen or other systems) herbicide applications are feasible for post-harvest control of Russian thistle in arid and semi-arid regions of the PNW (Riar et al. 2011). Greater than 90% control was achieved with a light-activated sensor-controlled sprayer using paraquat + diuron, and chemical use was reduced by 42% compared to broadcast applications. Control with glyphosate + 2,4-D was unacceptable regardless of applicator type. Sensor-based technology can be easily calibrated for Russian thistle because its bright-colored leaves contrast greatly with the brown-gold of the soil-wheat stubble post-harvest background. Small plants (<3 inches tall and <1.5 inches diameter) were missed by the sensor applicator, but these plants were not mature or flowering, and additional growth or seed production after the herbicide treatment was thought to be insignificant (Young et al. 2008).

Jointed Goatgrass ● ▲ ■

Jointed goatgrass (*Aegilops cylindrica*) is a winter annual grass weed of importance in small grain production systems because it is closely related to wheat. Jointed goatgrass, as a winter annual weed, is very competitive with winter wheat. Climate can affect how jointed goatgrass competes with wheat. In a dry year, winter wheat yield loss ranged from 55% to 84%, while in a wet year, grain yield was reduced by 30% to 40% (Ogg and Seefeldt 1999).

Rotations that avoid winter cereals for more than 3 years in wet climates (>18 inches precipitation) ●, or more than 6 years in drier climates (<18 inches precipitation) ■ are required for reducing goatgrass seed germination to less than 0.1% (Cook and Veseth 1991). Integrated planting strategies for winter wheat that can help reduce jointed goatgrass in grain-fallow regions include planting competitive varieties, increasing seeding rates and seed sizes, and fertilizing nitrogen, sulfur, and starter phosphorus with the seed (Young et al. 2010). ■ Combining a tall wheat cultivar and increased seeding rate with nitrogen fertilizer banded by the seed reduced jointed goatgrass densities 45% to 60% compared to conventional practices (Young et al. 2010). In all regions, the spring wheat-fallow-winter wheat rotation reduced jointed goatgrass **dockage** most consistently (Young et al. 2010). In the PNW, winter wheat varieties with rapid height gain and greater height are more competitive against jointed goatgrass and reduce jointed goatgrass seed production, particularly in drier years (<12 inches precipitation) (Ogg and Seefeldt 1999). ■

Spring crop rotations are important for jointed goatgrass management and are effective at preventing viable weed seed production. Spring-germinated jointed goatgrass does not compete well with spring wheat. Delaying spring wheat planting by 13 to 15 days generally did not decrease yields significantly and has been shown to prevent the production of viable seed from spring-germinated jointed goatgrass in plot studies in various precipitation zones across the PNW. Use of fall and spring tillage and herbicide applications before planting spring crops controlled jointed goatgrass plants and spikelets over time (Young et al. 2003)

Jointed goatgrass can be selectively managed by growing imazamox-resistant wheat without causing crop injury (Ball et al. 1999). There are considerable plant-back restrictions in the inland PNW following an application of imazamox, effectively forcing the grower to use imazamox-resistant rotational crops to minimize crop injury in rotation. The system is also expensive. As a consequence, it is often far more economical to hand-weed small populations when discovered and only use imazamox-resistant wheat for large, dense populations as part of an integrated management strategy.

Italian Ryegrass ●

Italian ryegrass (*Lolium perenne* var. *multiflorum* Lam.) is a cool season bunchgrass and a major annual weed in inland PNW cropping systems (Hulting et al. 2012). Italian ryegrass causes economic losses because it competes with winter wheat, can contribute to cereal lodging, and can cause lower harvest grain quality and higher dockage (Hulting et al. 2012).

Long-term planning is essential to managing Italian ryegrass. It is found primarily in the high precipitation zone in eastern Washington. ● The seed are viable for 3 to 5 years, depending on placement in the soil. Deep burial will likely reduce seed persistence, but shallow incorporation may increase it. The seed are moderately persistent on the seed head, making it feasible to destroy the seed after it is set but before dehiscence. An infestation can result from germination of only 2% to 4% of seed present in the soil (Unger et al. 2012). Italian ryegrass is competitive with winter wheat for nutrients, water, space, and light (Carson et al. 1999; Hashem et al. 1998; Hulting 2014). Cultural inputs for Italian ryegrass management are necessary for satisfactory management. Crop rotation is the most effective input for managing Italian ryegrass, and a 4-year or longer rotation is likely required. However, no long-term rotational studies have been conducted to address Italian ryegrass management in the inland PNW. The winter wheat-spring wheat-spring pulse crop rotation is likely inadequate for managing ryegrass. A second consecutive year of a broadleaf crop, like canola, would increase the efficacy of crop rotation for management of ryegrass, but only if the ryegrass is effectively managed in the pulse and spring wheat crops. Glyphosate resistant spring canola is an excellent tool for Italian ryegrass management in a rotation. Conventional canola is no different than a pulse since the same herbicide mode of action would be used in each crop.

Planting date, seeding rate, row spacing, a competitive cultivar, and fertilizer placement all play a role in managing Italian ryegrass. Growers tend to think in terms of seed weight per acre but are encouraged to begin to think about plants per square foot, and the seed required to achieve a competitive crop plant density. The crop plant population required for optimal economic return is usually considerably less than the seeding rate required for optimal crop competition. Pulse seeding rates are likely half of what they need to be for achieving a competitive stand. Typical row spacing for lentil and pea are also likely too wide.

The most compelling new tool for seed management is the Harrington Seed Destructor, a tool that destroys the seed in the harvest process. Developed to manage a similar weed called rigid ryegrass, the Harrington Seed Destructor grinds weed seed during the harvest process (Harrington and Powles 2012).

No-till and minimum tillage have increased reliance on postemergence herbicide applications in winter wheat production in order to manage Italian ryegrass and broadleaf weeds. As a result, Italian ryegrass populations in the PNW (and other regions) have developed cross- and multiple-herbicide resistance to a number of herbicide groups, including ACCase inhibitors (Group 1/A), acetolactate synthase–inhibiting herbicides (Group 2/B), photosystem II inhibitors (Group 5), glyphosate (Group 8/G), and very-long-chain fatty acid synthesis inhibitors (Group 15/K) (Hulting et al. 2012; Perez-Jones et al. 2007; Rauch et al. 2010).

Chemical inputs must include effective herbicides—often an effective herbicide program includes both preeemergence and spring-applied postemergence herbicides. Growers should make sure that the ryegrass under management is not resistant to the selected herbicide treatments. Products containing pyroxasulfone or flufenecet are required for successful management of Italian ryegrass in winter wheat as Italian ryegrass has not yet developed widespread resistance to these herbicide materials. They are applied in the fall according to the label. The product that contains flufenecet (Axiom) also contains metribuzin, and therefore cannot be applied until the wheat has two true leaves. Metribuzin can improve control achieved with pyroxasulfone. Pyroxasulfone can be applied immediately after the winter wheat is planted as a preemergence treatment. Continued experimentation with pyroxasulfone use in winter wheat will provide better understanding of its utility for control of other important grass and broadleaf weeds in cereal cropping systems. Integrated Italian ryegrass management strategies would be necessary in order to maintain efficacy of pyroxasulfone in the long term (Hulting et al. 2012).

Postemergence herbicides should be rotated. Group 1/A and Group 2/B herbicides cannot be mixed to improve Italian ryegrass control because of antagonism, so rotating products containing pyroxsulam and mesosulfuron with pinoxaden or clodinafop is critical. Herbicides used for Italian ryegrass management should be applied alone—applying grass weed management herbicides with broadleaf herbicides reduces efficacy on grass weeds. Plant size should be monitored carefully, and an assessment of the likelihood of continued germination should be made prior to the decision to apply herbicides. Herbicides should be applied when the target species is of appropriate size. Don't wait for the broadleaf weeds to germinate, or vice versa. Utilizing full rates of preemergence herbicides for grass control in broadleaf crops is also essential. Employing effective chemical weed management tools in rotation by utilizing metolachlor or dimethenamid is critical for long-term management of Italian ryegrass.

Summary

IWM strategies are critical for effective long-term management of weeds in the agroecosystem. Growers are encouraged to learn more about the biology and ecology of the weeds they are managing, and to use that knowledge to exploit vulnerable life stages of the weed for control. Growers should think critically about inputs employed for crop production in the context of weed management. Herbicides are an important part of an IWM strategy, but no herbicide can keep a crop weed-free for the entire season. A good competitive crop will always be the best weed management practice, and a sequence of successful crop rotations are critical for managing weeds in the inland PNW.

Additional Resources

Weed Management Handbook

https://pnwhandbooks.org/weed

The Weed Management Handbook is part of the Pacific Northwest Pest Management Handbooks publication series. Updated yearly, the site contains weed management information on most crops produced in the PNW.

Oregon State University Weed Science webpage

http://horticulture.oregonstate.edu/group/weed-science

http://cropandsoil.oregonstate.edu/group/weed-science

The Oregon State University Weed Science webpage is a clearinghouse for weed science-related information. The site contains comprehensive information for weed managers in Oregon as well as links to resources for the PNW.

Washington State University Weed Resources webpage

http://smallgrains.wsu.edu/weed-resources

The Washington State University Weed Resources webpage is a clearinghouse for weed science-related information. Part of the Wheat and Small Grains website, the Weed Resources webpage includes timely and frequently updated information on common weeds, regional PNW publications from both Oregon State University and the University of Idaho, weed identification services, herbicide resistance testing services, and decision support tools.

University of Idaho Weed Resources websites

http://www.cals.uidaho.edu/weeds2/IWR/iwr-v6_website/

https://www.uidaho.edu/cals/kimberly-research-and-extension-center/weed-science

University of Idaho hosts two websites: one focused on invasive weeds and one focused on southern Idaho weed management.

Herbicide Labels

CDMS: ***http://www.cdms.net***

Green Book: ***http://www.greenbook.net/***

Herbicide labels can be found at two sites in searchable databases. The CDMS site has a very powerful advanced search that requires registration.

National and Regional Organizations that Host Weed Science Information

American Society of Agronomy (ASA)
http://www.agronomy.org/

Weed Science Society of America (WSSA)
http://www.wssa.net/

Western Society of Weed Science (WSWS)
http://www.wsweedscience.org/

Western Region Sustainable Agriculture Research and Education (WSARE)
http://www.westernsare.org/

Education and Online Lessons

Crop Adviser Institute
http://www.cai.iastate.edu/

Online Crop Technology Lessons
http://croptechnology.unl.edu/pages/

Herbicide Resistance

International Survey of Herbicide Resistant Weeds
http://www.weedscience.org

Herbicide Resistance Action Committee
http://www.hracglobal.com/

Weed ID Resources and Weed Photos

PNW Weed Management Weed ID collection
http://pnwpest.org/pnw/weeds?weeds/id/index.html

UC IPM Weed Photo Gallery
http://www.ipm.ucdavis.edu/PMG/weeds_common.html

WSSA Weed Photo Album
http://wssa.net/wssa/weed/weed-identification/

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