Cover Crops Factsheet Series

Cover Crops as a Weed Management Tool

1. What is a cover crop?

A cover crop is any plant or crop grown when the ground would otherwise be fallow (bare). A cover crop is generally not harvested but rather is grown for ecological and environmental benefits it can provide to a cropping system. There are many ways that cover crops can be introduced into a cropping system; frost seeding, interseeding, companion seeding, and postharvest seeding to name just a few. In addition, some farmers do graze cover crops or harvest them for forage or seed depending on need. Review USDA-RMA guidelines for your state/region to ensure you are following harvesting restrictions that may apply if you participate in federal crop insurance programs. Regional cover crop organizations in the U.S. help researchers, educators, ag professionals and growers connect and manage cover crops on a regional scale. To learn more about cover crop benefits and general management in your region, visit them using the links below:

- Southern Cover Crops Council: https://southerncovercrops.org/
- Northeast Cover Crops Council: https://northeastcovercrops.com/
- Midwest Cover Crops Council: https://www.midwestcovercrops.org/
- Western Cover Crops Council: https://westerncovercrops.org/

A crimson clover-cereal rye cover crop mix. (Photo credit: Emily Unglesbee, GROW)

2. Why grow a cover crop?

Although the focus of this website is the impact on weed management, cover crops provide many benefits to an agricultural system. These include reducing soil erosion and increasing water infiltration, improving soil quality, retaining plant nutrients, adding nitrogen with legumes, breaking disease and insect pest life cycles, enhancing biodiversity, creating wildlife habitat, and attracting beneficial insects such as pollinators. Relative to weeds, cover crops can help reduce weed problems both when the cover is alive and growing as well as after termination, when it creates a mulch on the surface of the soil.

3. Are there any risks or unwanted effects with cover crops?

Despite the many benefits of cover crops, there are also potential risks. Cover crops may provide overwintering habitat for certain insect pests or serve as hosts for some plant pathogens. Some cover crops are more difficult to terminate, such as annual ryegrass. Incomplete termination can interfere with planting or create competition with subsequent cash crops, and may allow cover crops to set seed, resulting in future volunteer cover crop problems. Other potential risks include nutrient immobilization (nitrogen), moisture depletion, and an additional expense for seed, management, and potential need for specialized equipment.

4. What impacts do cover crops have on weeds?

How do cover crops contribute to weed management?

Cover crops contribute to weed management at multiple points in the life cycle of annual weeds (Figure 2). Sowing cover crops into a seedbed after removing weeds via tillage or burndown herbicides is the first step in maximizing the weed suppression benefits of cover crops. When actively growing, cover crops compete with weeds for space, light, nutrients, and water, depriving weeds of these needed resources. Cover crops alter the environmental conditions at the soil surface, which can prevent or delay germination of some weed species. Certain cover crop species release compounds that prevent weed seed germination or kill weed seedlings (i.e., allelopathy). (See more from GROW on this phenomenon here: https://growiwm.org/the-hunt-to-make-cereal-rye-more-competitive-above-below-ground/). These compounds are released by living and decaying cover crops and only persist for a few weeks once terminated. The use of cover crops with potent allelopathy could benefit weed suppression and breeding and selecting cover crops with this potential trait continues. However, a recent meta-analysis concluded that allelopathic effects from the cover crops used today are variable and unpredictable under many management scenarios.

Terminating cover crops with broad spectrum herbicides or tillage presents another opportunity to control weeds in the cover crop stand. Finally, a high biomass cover crop mulch smothers weeds by creating a physical barrier and by blocking light and altering the surface microenvironment.

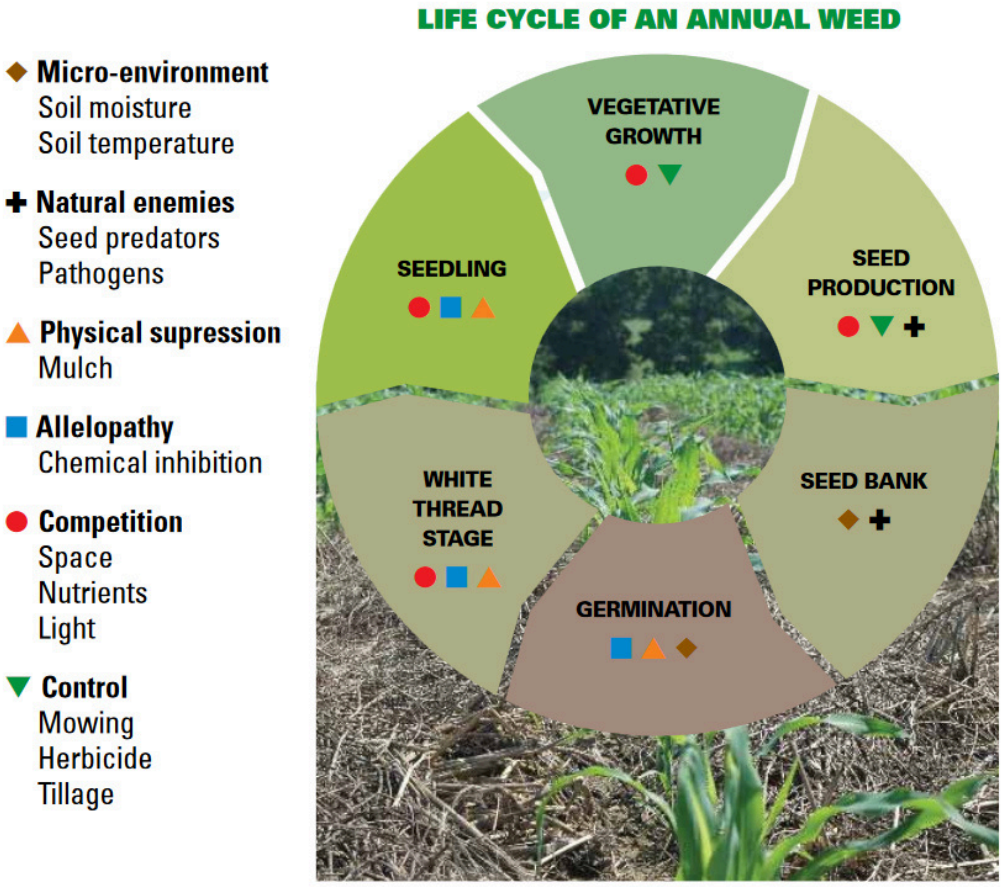


Figure 2. Cover crops can target all stages of the annual weed life cycle. For optimal weed control, select and manage cover crops that align with the life stages of the targeted weeds. (Diagram from Nord, et al. 2010 UC210, Penn State).

4. What impacts do cover crops have on weeds? (cont.)

How do cover crops assist in herbicide-resistance (HR) management?

Cover crop use, in combination with other weed control methods, adds another tool and diversity to the weed management program. The more diverse a weed management program is, the less reliant it is on one or a few herbicides, and the less likely herbicide resistance is to evolve or spread. In addition, when cover crops reduce both weed numbers and size, they improve herbicide efficacy and lessen selection for herbicide resistant weeds.

Why do cover crops suppress rather than control weeds?

Herbicides are chemically designed to control (i.e., kill) weeds. Cover crops, however, are living organisms with the ability to compete with other species for different resources (light, water, nutrients). In general, cover crops can reduce the survival of weeds, or reduce the growth or competitiveness of weeds that survive in cover crops. By competing with weed species for resources, cover crops can reduce the success of weed emergence and stunt weed growth, reducing the potential for weeds to impact cash crop growth and yield. But cover crops can also have little to no effect on weed emergence, establishment and survival depending on weed species, cover crop selection, and management.

We say cover crops "suppress," rather than "control," weeds, because with the right management, we can reduce the weed population by 50% to 75%, but rarely achieve complete control. (Likewise, if a herbicide only achieves 50% to 75% weed control, that is also considered weed suppression, rather than control). Cover crops can also alter the soil environment where the weed seeds reside and reduce or suppress the germination and emergence of weeds. As a result, there can be fewer weeds. One way to observe these effects is for farmers to plant small test plots with cover crops and observe the size and density of weeds in the areas with cover crops compared to the areas without cover crops.

A thick mat of cereal rye residue suppressing weed emergence. (Photo credit: Claudio Rubione, GROW.)

4. What impacts do cover crops have on weeds? (cont.)

What weeds are good targets for suppression?

The target weeds should align with the life cycle of the cover crops. For example, winter annual weeds such as horseweed/marestail, chickweeds and shepherd's-purse are good candidates for winter annual cover crops seeded in late summer and fall.
As an example, cereal rye plus hairy vetch established in the fall reduced horseweed density when measured at spring burndown in a Penn State study (Figure 3).

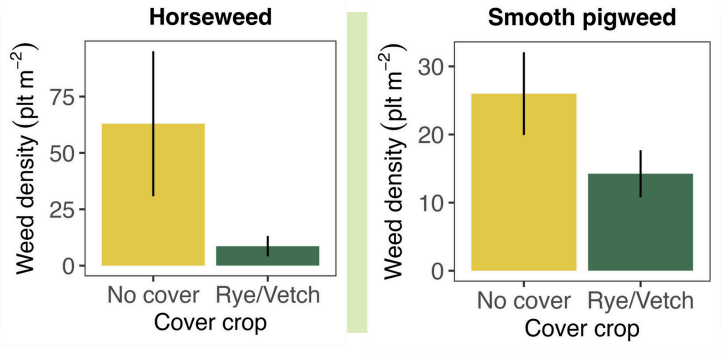


Figure 3. Effect of a rye/vetch mixture on horseweed density at spring burndown (left) and redroot pigweed density (right). Vertical bars represent variability around an average. (Bunchek et al. 2020 – Figure credit: J. Wallace, Penn State University).

Small-seeded summer annual broadleaves such as the pigweeds and common lambsquarters are also good targets for cover crops that can overwinter and produce sufficient biomass in the spring, although cover crops tend to be less impactful and require more intense management to target these weeds. In the same Penn State study, the cereal rye/hairy vetch cover crop also reduced redroot pigweed density when measured after cash crop planting at the time of the POST herbicide application. In general, annual and perennial grasses are more difficult to suppress with cover crops.

Larger-seeded broadleaf weeds are also impacted less by cover crops. In another study from Penn State, larger-seeded broadleaves including burcucumber, common ragweed, annual morningglory, and velvetleaf emerged and survived more successfully through a cereal rye mulch than the smaller seeded Palmer amaranth. Only Palmer amaranth survival was reduced by more than 50% compared to no cover-crop.

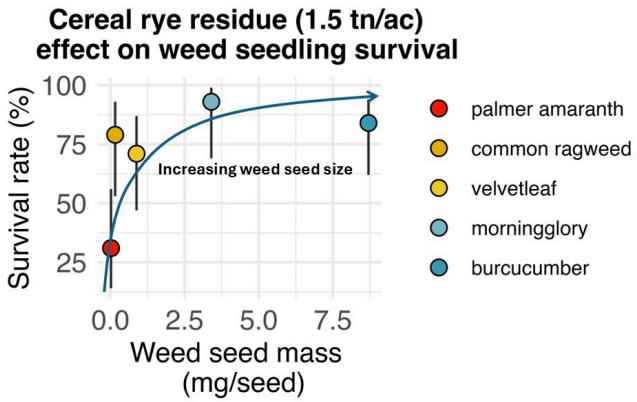


Figure 4. Cereal rye dry matter (3,000 lb/acre) reduced Palmer amaranth seedling survival compared to several larger-seeded broadleaf weeds. Vertical bars represent variability around an average. (Ficks et al. 2022 – Figure credit: J. Wallace, Penn State University).

4. What impacts do cover crops have on weeds? (cont.)

Examples of the difference in cover crop weed suppression between large-seeded weeds (giant ragweed) and small-seeded weeds (waterhemp). (Photo credit: John Wallace, Penn State.)

Can cover crops suppress perennial weeds?

For suppression of perennial weeds, cover crops must be used in conjunction with other weed control tactics such as tillage, mowing, and/or herbicides. This practice is more common in organic systems, which don't have herbicide options, because it often means leaving a field fallow for a season to plant and manage the cover crop to help reduce the problem weeds. For example, Canada thistle populations can be reduced by planting a summer annual cover crop like Sudangrass, then mowing it (and the weeds in it) several times over the summer. Fall seeded winter annual cover crops like cereal rye or other winter grains can also help suppress perennials such as Canada thistle and the bindweeds by competition while growing in the fall and spring prior to cash crop establishment.

5. Do all cover crops suppress weeds equally well?

How do I select the best cover crop for weed suppression?

The best cover crops for weed suppression emerge and grow quickly, rapidly shade the ground, produce large amounts of biomass, and have lasting residue that acts as a mulch after the cover crop has been terminated. In late summer and fall, grass cover crop species like cereal rye, wheat, and oats suppress weeds better than legumes. Brassicas such as forage radish can provide good weed suppression through early spring when planted in late summer. In general, legume cover crops are less competitive with weeds because they can be slow to establish, and some weeds take advantage of their ability to fix nitrogen, which the weeds can use to become more competitive. Farmers that want to fix nitrogen and suppress weeds can plant a mixture of grass and legumes, such as cereal rye plus hairy vetch or crimson clover.

See a farmer case study from a Virginia grower here: https://www.youtube.com/watch?v=ywqnhDe8nGY

See a Virginia Tech study on grass-legume cover crop mixes here: https://growiwm.org/mix-cereal-rye-with-hairy-vetch-to-cash-in-on-cover-crop-benefits/

Use the **Cover Crop Species Selector** tool to find the right species for your farm's climate, geography and goals:

https://covercrop-selector.org/

Large-seeded summer annual and creeping perennial weeds are more challenging to manage using cover crops. Good suppression of these weeds with cover crops may require including a summer fallow period and using competitive warm season species such as sorghum-sudangrass or forage sorghum seeded in early summer and periodically mowing to help reduce certain weed populations. These tactics will likely disrupt the production of the cash crop and are more common in organic vegetable production systems where weed management options are fewer and the organic cash crops more valuable than in conventional grain production systems.

A mix of cereal rye and hairy vetch in a Virginia study showed good success both suppressing weeds and fixing nitrogen, but required extra management, including two termination passes. (Photo credit: Jenna Beville, VA Tech)

5. Do all cover crops suppress weeds equally well? (cont.)

Are cover crop mixtures better than monocultures?

Cover crop mixtures can provide more benefits than monocultures but can also be more costly and difficult to manage. Many growers like multi-species mixtures for various reasons including increased productivity, improved soil health, better nutrient cycling, reduced compaction, habitat for pollinators and other beneficial insects, and added insurance against adverse weather that might injure or kill single species.

However, mixtures may not always make the most sense when weed suppression is a primary goal. In general, previous research has demonstrated that one or two cover crop species that establish quickly, cover the soil, and produce large amounts of biomass are key requirements for weed suppression. Small grains such as cereal rye are often recommended for their fast establishment and high biomass production.

Several studies have compared individual cover crop species to cover crop mixtures for their potential to provide various ecosystem services. A New Hampshire study assessed the weed suppression effects of cover crop mixtures versus monocultures at the time of cover crop termination. The scientists reported that mixtures were never more weed suppressive than the most weed-suppressive cover crop grown as a monoculture, and the more diverse mixtures (14 species) never outperformed the less diverse mixtures (5 or 6 species).

In Pennsylvania, grass monocultures (oats and cereal rye) and mixtures containing grass cover crops were consistently more weed suppressive than brassica (daikon radish and canola) and legume (pea and medium red clover) cover crops. And finally, in eastern Canada, the most biomass-producing cover crops tended to be the most weed suppressive regardless of whether they were monocultures or mixtures, and both productivity and weed suppression were dependent on species selection.

To create a weed-suppressive cover crop mixture, Penn State Extension recommends starting with one or two species that will cover the soil rapidly, then add more species according to your other goals (see Image below). Remember, a carefully planned mixture of a few complementary species can provide the same or more services than a mixture with many species.

Cover crop mixtures need to be well balanced to prevent one species from outcompeting the others and failing to produce the expected benefits. (Photo Credit: Emily Unglesbee, GROW)

This 4-species mix consists of species with complementary growth forms: cereal rye and canola transition from short, dense canopies to tall, open canopies in the late spring, Austrian winter pea is vining, and red clover remains short and dense. (Photo credit: PSU.)

6. How much cover crop biomass do I need for weed suppression?

Once the cover is terminated, the amount of cover crop biomass or dead mulch is the key to weed suppression. Weed suppression from cover crops increases as biomass increases, up to a certain level. The amount of dead biomass or mulch necessary to suppress summer annual weeds varies by both region and also weed species. As explained in #4 previously, small-seeded broadleaves are most sensitive to suppression with mulch, while larger-seeded broadleaves and annual grasses are more difficult to suppress.

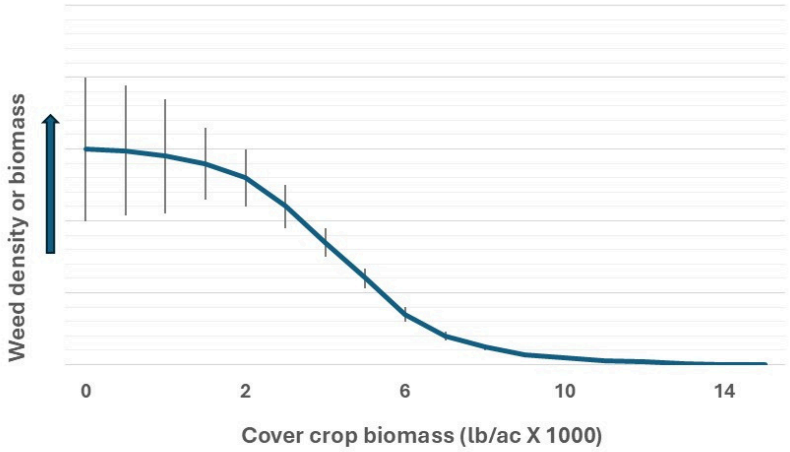


Figure 5. The theoretical effect of cover crop biomass or mulch on weed density early season or biomass at the end of the growing season based on empirical observations. With more cover crop mulch at the time of termination, weed density or biomass is consistently reduced. Vertical bars represent the potential error or variability around an average, so with no or little mulch, weed density or biomass can vary greatly. (Figure credit: W. Curran, Penn State University).

Why does cover crop weed suppression vary by region?

Geography (i.e., how far north or south a location is) affects climate, which in turn impacts the growth and development of cover crops. Differences in soil type and productivity across regions also contributes to differences in cover crop growth and yield. The southeastern US is typically warm and moist during the growing season which generally increases cover crop growth and productivity. In contrast, northern latitudes are cooler and have shorter growing seasons which can delay cover crop establishment in the fall and reduce the potential for aboveground biomass in the spring. The weed species that are commonly found can also be different across regions. In the southeast region, there are often more diverse weed populations; they may begin emerging in early spring and continue emerging longer into the growing season. Herbicide-resistant Palmer amaranth has become a major weed problem throughout the Southeast. In more northern climates, weeds often do not emerge until mid to late spring, and emergence periods are typically shorter than in the south. Waterhemp and other pigweed species and common lambsquarters are more common weeds in the northern Corn Belt. The differences in temperature, rainfall, and weed spectrum also impact the performance of cover crops, sometimes increasing the potential for suppression of some weed species and at other times reducing the opportunity for others.

6. How much cover crop biomass do I need for weed suppression? (cont.)

Below is a summary of general research-based recommendations on cover crop biomass needed for weed suppression in the different regions of the U.S.

Northeastern U.S.
Research suggests that in the northeastern U.S., a cereal rye cover crop that produces at least 7,000 lbs per acre of biomass can provide good (greater than 80%) weed suppression. This level of biomass production requires prolonging cover crop duration in the field through earlier planting and/or later termination, using practices such as planting green.

Southern U.S.
In the southeastern U.S., cover crops have been found to reduce weed density (meaning the number of weeds in a field) but not necessarily weed biomass (meaning the total amount of plant matter the weeds produced by the end of the season). That may be due to higher temperatures and plentiful moisture allowing the lowered number of weed escapes to recover and thrive, as well as shorter persistence of the cover crop residues/mulch. On average, research suggests that about 6,000 lbs per acre of cover crop biomass is needed to reduce weed density by 50% in this region. This level of cover crop biomass production can be expected under southern U.S. growing conditions, using typical cover crops such as cereal rye and standard management practices.

Midwestern U.S.
In the midwestern U.S., research has shown that grass (though not other) cover crops can reduce weed biomass (the total amount of plant matter), but not density (the number of weeds in a field). Research suggests that it takes about 4,500 lbs per acre of cover crop biomass to reduce weed biomass by 75%. Keep in mind that this level of cover crop biomass production may require earlier cover crop planting and later termination than the standard practice in this region. So farmers who want to use cover crops for weed suppression need to consider ways to make space in their rotation to give cover crops more growing time in the field.

Western U.S.
In the western U.S., good weed suppression (meaning a 50% reduction in biomass of some weeds) can be seen with as little as 2,200 lbs per acre of cover crop biomass. However, soil-water management in dryland systems is often a serious concern in this region. Some research suggests that adding a cover crop in the fallow period of a rotation at least once very three years can balance soil moisture and weed suppression concerns. But growers must carefully evaluate soil moisture levels and forecasted precipitation trends in their region each spring before seeding cover crops. A strategy known as flex-fallow cover cropping, where cover crops are planted only in wet years and left fallow when conditions are dry, is being promoted in western Kansas.

6. How much cover crop biomass do I need for weed suppression? (cont.)

How can I estimate cover crop biomass in my fields?

A relatively uniform cover crop without large gaps of missing plants or stunted areas is necessary to suppress weeds. For a uniform healthy cover crop stand, the most accurate way to estimate biomass is to collect above ground samples in several areas of the field, dry them in the oven at relatively low temperature (<150 F), and weigh the residue/material. This requires several tools to take accurate samples. At a minimum, some flags, a tape measure, hedge clippers, some paper bags, and a scale capable of weighing biomass in ounces or grams are needed. Once your samples are oven dry, you can calculate how much dry matter you have and convert it to lb/acre. Healthy mature cover crops will produce between 2,000 and 10,000 lbs of dry matter per acre.

Watch a video on How to Sample Cover Crop Biomass at: **https://www.youtube.com/watch?v=C7x36MVsq5U**

Some useful conversions for estimating cover crop biomass in lb/acre.

- 1 acre = 4,840 yd2 = 43,560 ft2
- 1 lb = 16 oz = 454 grams
- 1 oz = 28 grams
- 2,000 lb/acre dry biomass = 0.046 lb/ft2 = 0.74 oz/ft2 = 21 grams/ft2
- 10,000 lb/acre dry biomass = 0.23 lb/ft2 = 3.7 oz/ft2 = 104 grams/ft2

Here are several useful links to instructions for estimating cover crop biomass.

- USDA-NRCS based in Iowa developed a factsheet describing the cut and weigh method for collecting and estimating biomass or dry matter: **https://www.nrcs.usda.gov/sites/default/files/2024-10/EstimatingCoverCropBiomass.pdf**

- Dr. Eric Brennen with the USDA-ARS in the Salinas Valley of California describes an effective way to estimate cereal cover crop biomass based on shoot or stem length. This eight minute video (**https://www.youtube.com/watch?v=QwcFW30ILMQ**) describes the method he developed using cereal rye or triticale. His results and recommendations currently only include these two cereals and are most suitable for cover crop use in California vegetable systems, but do have implications for other production systems and regions. Here is the paper that describes the research that helped develop the recommendations: **https://acsess.onlinelibrary.wiley.com/doi/full/10.1002/ael2.20099**

- Future technology is in development in both the public and private sphere to allow growers to estimate cover crop biomass based on 3D-imaging via camera sensors mounted on tractors or research plot equipment. Specifically, researchers with USDA and Precision Sustainable Agriculture are developing an inexpensive, efficient, and highly accurate way for growers to estimate cover crop biomass, alongside real-time weed identification: **https://www.precisionsustainableag.org**

6. How much cover crop biomass do I need for weed suppression? (cont.)

How does cover crop management affect weed suppression?

Management of the preceding and following cash crops will dictate cover crop management (such as planting and termination dates) and biomass production for weed suppression. Early planting of cover crops produces more biomass and delivers better weed suppression than late planting. In Pennsylvania, a cereal rye cover crop planted on August 25 produced almost 2,500 lbs/acre more biomass on average than rye planted on October 15. In Alabama, cereal rye biomass production increased on average by 170% when seeded in late October compared to early December. Soil fertility and added nitrogen can sometimes also influence productivity; in the same study, nitrogen increased rye biomass production, but the effect decreased with later planting dates. Low fertility and especially low nitrogen levels can limit growth and development of both cereals and some non-grasses.

Termination timing is even more crucial for weed suppression. For example, a number of studies show that cereal rye terminated at the tillering stage results in low rye biomass and consequently less weed suppression. In the Pennsylvania study mentioned above, rye more than doubled its biomass between the beginning and end of May.

In another Pennsylvania study, rye biomass again almost doubled by delaying termination one to three weeks by planting green instead of terminating preplant. Delaying cover crop termination until close to cash crop planting gives the cover crop the maximum amount of time possible to accumulate biomass, which is key to suppressing weeds through direct competition and from the dead cover crop mulch. Early seeding dates combined with later termination dates maximize biomass production, though a later termination date can partly compensate for a later planting date. A meta-analysis focused on Amaranthus species and cover crop management using data collected across the corn and soybean growing regions of the US showed the benefits of early seeding and later termination.

Figure 5. The theoretical effect of cover crop biomass or mulch on weed density early season or biomass at the end of the growing season based on empirical observations. With more cover crop mulch at the time of termination, weed density or biomass is consistently reduced. Vertical bars represent the potential error or variability around an average, so with no or little mulch, weed density or biomass can vary greatly. (Figure credit: W. Curran, Penn State University).

6. How much cover crop biomass do I need for weed suppression? (cont.)

Cover crop planting methods matter, too; drilling cover crops rather than broadcast seeding generally results in better stands and more biomass. In a Maryland study, drill seeding or broadcast plus incorporation consistently had better cereal rye seedling emergence than broadcasting without incorporation. In Kentucky, drill seeding cereal rye led to higher plant density, cover crop biomass, percent ground cover, and lower weed biomass when fall soil conditions were dry. Their results also showed that stand establishment was more similar when soil moisture conditions were good at the time of cover crop establishment.

The method of cover crop termination can also greatly influence weed suppression. No-till termination leaves the residues on the surface of the soil producing a mulch that can suppress weed emergence and growth. Termination with tillage incorporates the crop residues as well as any emerged weeds that are present, but the soil disturbance mostly eliminates any weed suppression benefit coming from the cover crop. Mowing the cover crop can control or suppress emerged weeds and, depending on the type of mower, can leave cover crop residues on the soil surface. Flail mowers tend to be better than rotary or other types of mowers at more evenly distributing cover crop residues. Chopped or cut up pieces of residue degrade more quickly than whole residues left in place and can sometimes be more challenging for planting the subsequent cash crop.

Should cover crop seeding rate be increased for delayed seeding?

The answer to this question depends on geography and the cover crop species in question. For example, increasing the seeding rate increases hairy vetch biomass up until a cutoff of September 15 (for early-terminated vetch) in New York, after which increased seeding rates do not make up for later planting dates. In Maryland, the same was estimated to be true up until October 25. Note that cover crop biomass is determined by soil fertility, planting and termination dates, and growing degree days as well as seeding rate (https://growiwm.org/do-high-cover-crop-seeding-rates-improve-weed-control/). With cereal rye, seeding rate did not influence spring biomass accumulation in two different studies conducted in the Mid-Atlantic region, but late seeding was not compared to earlier seeding. See the cover crop seeding rate article from Penn State for more information about selecting rates for the Mid-Atlantic region: https://extension.psu.edu/cover-crop-seeding-rates. In Alabama, planting in October versus December impacted biomass production, but increased seeding rate did not affect biomass production.

Early termination of a cover crop in the spring reduces the risk of the cover crop interfering with the planting of the following cash crop but also decreases the amount of biomass a cover crop can produce and thus decreases spring/summer weed suppression potential. The practice of “planting green” into a live cover crop can allow for both timely cash crop planting and a longer period of cover crop growth. This is discussed in **GROW’s Cover Crop Termination webpage: https://growiwm.org/cover-crop-termination/**

7. How do I establish a good cover crop for weed management?

When weed management is the main goal, timely cover crop establishment is a crucial first step for rapid growth and good biomass production. Seed cover crops using an effective method during the optimum planting window. As discussed previously, using a grain drill is one of the most effective planting methods for seeding most cover crops. More precision grass and legume boxes or a separate seeder (e.g., Brillion) can help ensure successful establishment of small-seeded grasses and legumes.

If the planting window is limited due to the short time between cash crop harvest and the onset of cold weather, consider interseeding into a standing cash crop using either a specialized drill or air seeder. Interseeding equipment and methods have been most refined for corn rotations, using either an interseeder planter which drills the seed (when corn is at the V4-V6 growth stage) or an air spreader which propels the seed through planting tubes using air flow (from corn stage V6 until a few days before harvest).

Both planting methods place the cover crop seed between the rows of corn. In both cases, the cover crop emerges and slowly establishes until after cash crop maturity and harvest, when the amount of light reaching the cover crop increases and promotes growth. Some cover crops are more shade tolerant than others and thus are a better choice for interseeding. For more information, see resources linked on the Midwest, West, Southern, and Northeast Cover Crops Council websites as well as the Penn State publication on interseeding cover crops in corn (https://extension.psu.edu/interseeding-cover-crops-in-corn-production).

8. How do I terminate my cover crop?

The choice of cover crop termination method depends on cover crop and crop rotation species, available equipment, and other goals. Cover crop termination methods fall into three general categories: winterkill, using herbicides, or mechanical methods.

For an overview of these options, as well as details on planting into high-residue, see the **GROW Cover Crop Termination webpage,** as well as a series of cover crop termination factsheets that provide best management practices for successfully terminating cover crops.

Go to www.growiwm.org/cover-crop-termination/

9. How do I prevent cover crops from becoming weeds?

How do cover crops become weeds?

Although cover crops can provide many benefits to a cropping system, they can also sometimes act like weeds. Remember that a weed is any plant growing where it is not wanted. Cover crops can become weeds several ways. Primarily, they can become weeds if they are allowed to go to seed and then volunteer in subsequent cash crops. Some cover crop and weed seeds have "hard seed" which means that the coat that covers the seed is impermeable to water until it is either physically damaged or decays allowing water uptake (imbibition). If hard seed lingers in the soil, it can germinate and emerge while a cash crop is growing. Cover crops can also become weeds if they are not successfully terminated (killed) prior to cash crop planting. Unsuccessful termination may result from environmental challenges (such as a wet spring) and management difficulties (such as failed termination methods and/or timing).

What cover crop species are least likely to become weeds?

Cover crop species least likely to volunteer or become weeds are those that are not allowed to flower and seed. When possible, select species that do not have hard seed properties or that winterkill (or are easily terminated in the spring) before they can set seed. Fall-seeded oats, daikon radish, and many other annuals that are not winter hardy in the northern half of the US can be safely seeded in late summer and fall without concern for becoming weeds the following year. In general, most of the cereals such as cereal rye, wheat, triticale, barley, and oats will not volunteer unless they are allowed to flower and seed. As for legumes, crimson and medium red clover, field peas, cowpeas, and several others are not likely to become weeds.

Cereal rye, crimson clover and field pea are among the cover crops least likely to become weeds, if managed properly. (Photo credits: Emily Unglesbee, GROW)

9. How do I prevent cover crops from becoming weeds? (cont.)

What species are most likely to become weeds?

The cover crop species most likely to become weeds are (1) those that have hard seed (such as rapeseed, hairy vetch, and some clovers such as white and sweet clover), (2) those that are seeded in early summer and grow quickly and set seed such as buckwheat, summer annual mustards (e.g., yellow and brown), and oats, and (3) those that can be difficult to control in the spring (such as some brassicas, some clovers and annual ryegrass). Cover crops that are difficult to control may survive termination, potentially leading to interference with planting the cash crop, competition with the cash crop, and the production of seed resulting in future weed problems (image 4). The difficulty in controlling volunteer cover crops depends on control options in the rotational cash crop. For instance, volunteer cereal rye is easy to control in corn or soybeans, but very difficult to control in winter wheat.

Volunteer cereal rye (left) and hairy vetch (right) in winter wheat. (Photo credits: C. Keene, Penn State)

What are the best methods to prevent cover crops from becoming weeds?

Choose cover crops that fit your cropping system. Farmers who grow small grains may choose a legume like crimson clover rather than hairy vetch because hairy vetch has hard seed and can volunteer in small grains, while crimson clover poses less risk of contaminating the harvested small grains. Mechanical termination using a roller-crimper without herbicide is only effective on a few species and must be done at the correct cover crop life cycle stage, or the cover crop may survive and produce seeds. If you are targeting timely cash crop planting in a conventional system, don't plan to use roller-crimping as your sole cover crop termination method. Without the addition of herbicides, it is unlikely that you will terminate your cover crop without some seeds being produced, even if you roll-crimp at the optimum time.

Terminate cover crops in a timely manner to avoid seed set. For example, buckwheat and yellow mustard should be terminated soon after bloom, which can occur within six to eight weeks of planting. Daikon radish planted in the late summer/fall will usually not survive the winter, while spring seeding bolts, flowers, and produces seed.

9. How do I prevent cover crops from becoming weeds? (cont.)

Use the appropriate method and timing to terminate cover crops. For example, while glyphosate alone can control most grass cover crops (such as cereal rye) in the spring, many legume cover crops require a tank mixture such as glyphosate + 2,4-D or dicamba.

Keep in mind that herbicide resistance has been documented in annual ryegrass. The resistant biotypes tend to have escaped from older cultivars that were used for forage or quick cover decades ago. Some resistant biotypes evolved as weeds due to herbicide use in cereal grains. Today's high-quality certified varieties produced for forage and cover crop should not have herbicide resistance. Even if resistance is not a concern, managing an annual ryegrass cover crop requires special consideration because of its inherent herbicide tolerance and annual ryegrass as a cover crop is not recommended in many regions where wheat and other cereal grains are commonly grown.

This factsheet describes in more detail how to manage an annual ryegrass cover crop prior to planting corn or soybean: https://growiwm.org/wp-content/uploads/2024/10/4-How-to-Control-Annual-Ryegrass.pdf.

Other potential herbicide resistant cover crops include those crops that have been developed through breeding efforts as herbicide-resistant/tolerant cultivars such as canola and soybean. When relying on herbicides to terminate a cover crop, be prepared to use a second termination method (or herbicide) if the first fails or else be prepared to control the cover crop (now weed) in the cash crop.

10. How do I integrate cover crops into an IWM program?

Using cover crops to help suppress weeds is only one piece of the puzzle in adopting a successful integrated weed management program. For most growers, additional cultural, chemical, and perhaps mechanical control tactics that are used to successfully manage weeds are still critical. Most cover crops should be managed no-till to capture their greatest weed suppression potential from the residue/mulch left on the soil surface after termination. This generally means relying on herbicides for both cover crop termination and for additional weed control. Combining herbicides with cover crops in no-till systems generally works well and adding cover crops to the rotation increases crop rotation diversity which adds cultural weed management to the system. No-till systems that do not rely on herbicides to control both cover crops and weeds are not common.

Adding effective mechanical control tactics is especially challenging in conventional no-till systems. Research at Penn State investigated using cover crops, reducing the amount of residual herbicide applied by banding over the crop row, and using high residue cultivation after crops and weed emerge in-between rows as IWM tactics in no-till corn and soybean. Results demonstrated that high-residue cultivation combined with herbicide banding and cover crops can provide similar weed control and cash crop yield as broadcast herbicide application in both corn and soybean. However, longer-term research conducted over a nine-year period concluded that this reduced herbicide-use tactic may lead to more weed problems over time. In general, reducing herbicide inputs by employing cover crops alone has had mixed results. For example, research at Virginia Tech concluded that a well-established cover crop prior to no-till soybean planting can substitute for the use of fall-applied residual herbicides to control late-fall and spring emerging horseweed, while in other research across the corn belt, cover cropping was insufficient to eliminate the use of fall or spring applied herbicides. If reducing herbicide use is a goal and/or herbicide resistant weeds are problematic, IWM tactics in addition to weed suppressive cover crops must be added to the system to help keep weeds in check. The complete list of available IWM tactics are discussed in more detail on the GROW website (https://growiwm.org/weed-management-toolbox/)

High-residue cultivation research at Penn State in a cereal rye terminated cover crop in soybean. These cultivators typically employ a single wide flat sweep between each crop row that runs 2 to 3 inches deep to undercut or dislodge emerged weeds. Inserted image in lower right is operating in a hairy vetch/triticale cover crop in corn. (Photo credit: Penn State)

10. How do I integrate cover crops into an IWM program? (cont.)

Rotational no-till systems that rely on cover crops have been developed in some organic cropping systems. The greatest success is in no-till soybean, where cereal rye is often managed using a roller-crimper to produce a weed suppressive cover crop mulch. No-till cover crop-based research in organic corn and other crops has also taken place at several institutions and on innovative farms, but achieving consistent cash crop yields compared to tillage-based organic systems remains challenging. Review the organic no-till soybean production guidelines from Penn State (https://extension.psu.edu/organic-no-till-soybean-production-in-pennsylvania-is-it-for-you) and the organic no-till planted soybean production guide from Cornell for more information about successful adoption of this cover crop-based system (https://www.newyorksoilhealth.org/resources/organic-no-till-soybean-guide/).

Cover crops and herbicide recommendations

Growers rely on herbicides, particularly in no-till crop production. In most circumstances, including cover crops for weed suppression still requires the use of herbicides, but some changes in management may be necessary. To start, consider what herbicides you used in the previous cash crop and make sure they don't persist and injure or kill your rotational cover crops (image 5). In general, small seeded legumes and brassicas tend to be most sensitive to some of the more persistent broadleaf herbicides used in row crop production. There are several useful articles published from various sources discussing herbicides to avoid when seeding certain cover crops. Here is a webinar sponsored by the Northeast Cover Crop Council featuring Dr. Mark VanGessel from the University of Delaware presenting some of these concerns: https://www.youtube.com/watch?v=U3Kc8lUkU5g.

Herbicide injury to cover crops interseeded in corn in a carryover experiment (left), and mesotrione carryover injury close-up in red clover (right). (Photo credits: W. Curran (left) and John Wallace (right), Penn State)

10. How do I integrate cover crops into an IWM program? (cont.)

The next consideration is choosing an effective burndown herbicide program that controls both the cover crops and emerged weeds. A recent series of short GROW factsheets was developed by Penn State that discusses herbicide management. See **Cover Crop Termination: How To Select Herbicide Programs** (https://growiwm.org/wp-content/uploads/2024/10/2-How-to-Select-Herbicide-Programs.pdf) for more information on herbicides for control of cover crops.

The third piece of the herbicide-cover crop question is more complicated and involves how both burndown and soil residual herbicides perform in combination with cover crops. Does the cover crop prevent the burndown herbicide from reaching emerged target weeds? Research from Penn State using water sensitive spray cards (TeeJet) showed that both cereal rye and a rye/vetch mixture interfered with herbicide deposition (Figure 6). The amount of interference depended on both cover crop species and cover biomass. Although less herbicide reached the soil (and the target weeds in theory) at the time the herbicide was applied, reduced herbicide performance was not observed in this experiment. Horseweed was a primary target and the study used a combination of glyphosate plus 2,4-D ester and standard Tee-Jet AIXR11002 tips applied at 20 GPA to control both cover crop and emerged weeds. Alternative herbicide selection and sprayer setup could impact burndown herbicide performance differently.

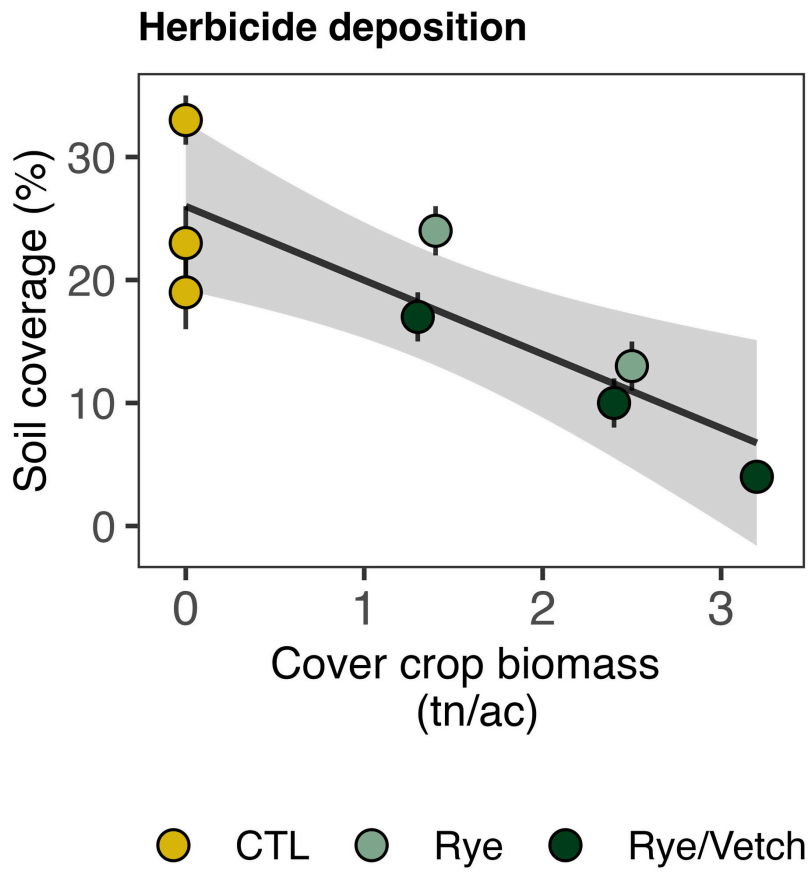


Figure 6. Effect of no cover (CTL), cereal rye, and cereal rye/hairy vetch biomass in tons/acre on herbicide deposition at the time of spring cash crop planting. Vertical bars represent the potential error or variability around an average (Bunchek et al. 2020 (Figure credit: John Wallace, Penn State University).

10. How do I integrate cover crops into an IWM program? (cont.)

What about soil-residual herbicides and cover crops? We know that herbicides can provide effective residual control of many problem weeds and that when cover crops are managed with weeds in mind, they can suppress emergence and growth. So, if you use cover crops for weed suppression, do you still need the full complement of residual herbicides? Several experiments have been investigating this question. A study led by University of Wisconsin researchers included scientists in KS, IL, WI, and PA reported that although a cereal rye cover crop (terminated preplant or planted green) reduced the amount of two residual PRE applied herbicides reaching the soil compared to no cover crop, it did not reduce pigweed control. The authors concluded that the combination of herbicide plus cover crop can be an effective IWM strategy in soybean.

Further research at Penn State examined additional herbicides and included a roller-crimped treatment either before or after herbicide application. They reported that in lower cover crop residue situations (≤2000 lb/acre), herbicide performance was mostly unaffected. With greater cover crop biomass (≥5000 lb/acre), herbicide loss was greater, and having a legume in the mix increased loss. However, like the multi-state study, the high biomass cover crop added weed suppression, which compensated for herbicide loss. When using a roller crimper in combination with residual herbicides, they recommend spraying the herbicide before using the roller crimper to reduce herbicide loss. They also recommend using residual herbicides early POST rather than at planting to help avoid losses. Learn more in this video about this graduate student led research at Penn State: https://www.youtube.com/watch?v=Pc099UJZWXw&t=9s.

PSU researchers measure herbicide interception by cover crop residue. (Photo credit: Claudio Rubione, GROW)

Does residual herbicide selection matter? In general, herbicides that are low in water solubility (fat loving or lipophilic) and that are less mobile in the soil may be more problematic when using high-residue cover crops than more soluble/mobile herbicides (water loving or hydrophilic). Herbicide wash-off with rainfall or by using irrigation from both living and dead plant residues requires greater amounts of moisture to move and mobilize low water soluble/low mobility herbicides off plant residues and into the soil where weed seeds germinate. For example, pendimethalin or Prowl is low in water solubility and mobility in contrast to S-metolachlor or Dual II Magnum which is moderate in both solubility and mobility. Although this has not been examined to our knowledge, it suggests that pendimethalin is less suitable than S-metolachlor for high residue cover cropping systems.

10. How do I integrate cover crops into an IWM program? (cont.)

Current research led by Penn State being conducted in the Northeast is investigating specific herbicide physical and chemical characteristics and the interaction with cover crop residues more closely and their results showed that herbicides that were neither highly lipophilic or hydrophilic when applied to cereal rye surface residues and subjected to simulated rainfall had the greatest wash-off potential among those herbicides tested. Preliminary results recommend that when using residual herbicides with high biomass cover crops, uniform spray coverage is key so attention to speed, carrier volume, boom height, and nozzle selection are all important. In addition, when possible, use herbicides that historically perform well in high residue no-till environments.

Can weed suppressive cover crops improve foliar herbicide performance? Many growers rely on these applications especially for control of emerged herbicide-resistant weeds in their major field crops. One advantage of using a weed suppressive cover crop mulch can be the ability to target fewer and smaller emerged weeds either in the burndown or postemergence application. In a Penn State study, a cereal rye/hairy vetch cover crop reduced the size and number of horseweed plants (Figure 7) at the time of burndown application. In the same study, it also reduced the size and frequency or occurrence of taller pigweed plants at the time of POST application (data not shown). This could allow delaying or even eliminating a post herbicide application because of fewer and smaller weeds and translate into direct cost savings as well as reducing the selection pressure for herbicide resistance by reducing herbicide inputs. In addition, the performance of foliar applied postemergence herbicides should remain either unaffected by the cover crop mulch or perhaps even improved by targeting fewer and smaller weeds.

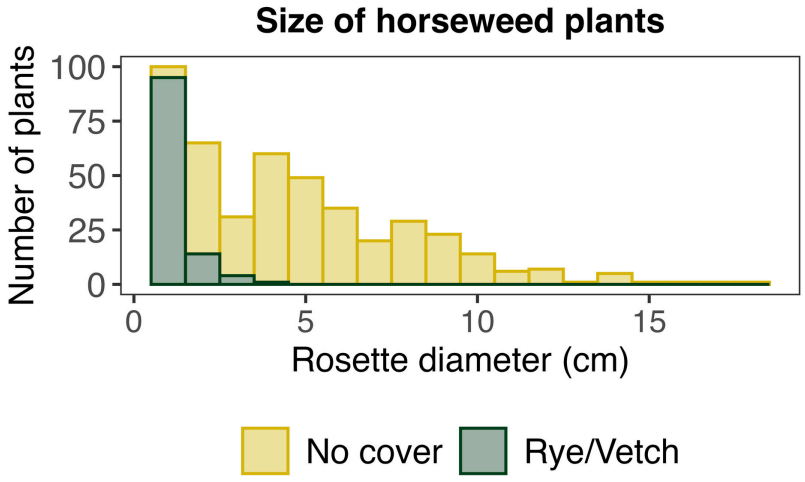
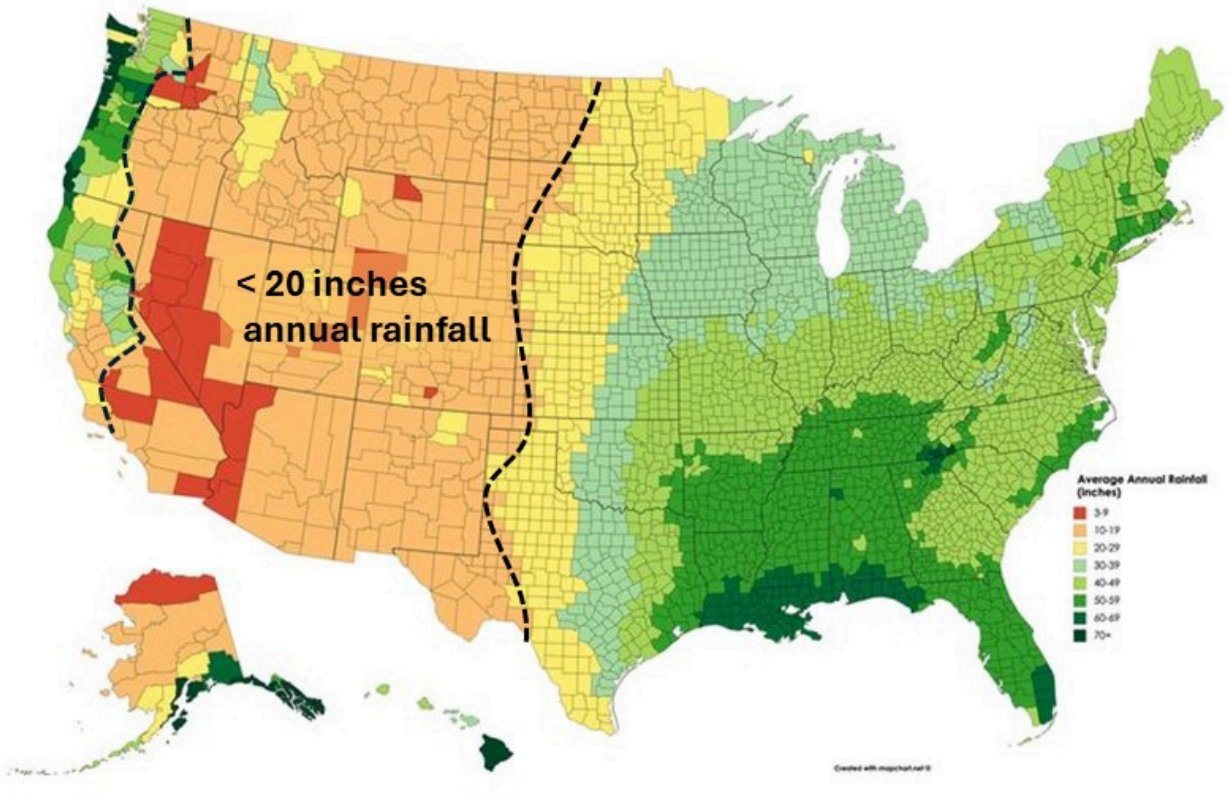


Figure 7. Effect of a rye/vetch mixture (dry matter averaged about 4,500 lb/acre across the experiment) on horseweed number and size at spring burndown. The cereal rye/hairy vetch reduced both the density and size of horseweed at the time of spring burndown (Bunchek et al. 2020; Figure credit: John Wallace, Penn State University).

Lastly, remember that the management goals for integrating cover crops and herbicides or other IWM tactics must be multi-tactic. Weed scientists at Penn State recently summarized the potential benefits of cover cropping and weed suppression using five key points. Cover crops can produce a measurable reduction in the (1) density of weed seedlings at the time of herbicide application, (2) rate of weed seedling emergence relative to crop emergence; (3) early-season weed growth rates (i.e., size and biomass production); (4) numbers of seeds produced by targeted species; and finally (5) dominance of 'adapted' or 'resistant' weed species on the farm. These five points can all be an advantage when designing your herbicide program or when implementing other control tactics. The bottom line is that thoughtful cover crop integration can be foundational to successful IWM.

11. How do I manage cover crops in moisture-limited regions?

Cover crop adoption in lower rainfall environments has been limited. Imagine a line running south from the Canadian border, through the central Dakotas and across western Nebraska, Kansas, and Texas (see below image). To the west of that line, annual precipitation is less than 20 inches, and dryland cropping systems typically include a fallow period to help conserve soil moisture for the subsequent cash crop. These fallow periods present the greatest opportunity for integrating cover crops into these dryland cropping systems. However, several published studies show that introducing or substituting those fallow periods with soil-building cover crops often reduces the yield potential of subsequent cash crops. In this geography, growing high biomass weed suppressive cover crops is not practical or recommended.



U.S. annual precipitation map, slightly modified. (Map credit: NOAA National Centers for Environmental Information: https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/county/mapping)

At the same time, dryland regions are plagued with increasing prevalence of multiple herbicide-resistant weeds like kochia, Palmer amaranth, and wild oats and managing these weeds during the moisture-conserving fallow period is critical. Uncontrolled weed infestations in fallow rotations can reduce available soil moisture and nutrients as well as add to the weed seedbank, negatively affecting subsequent cash crop yield. Weed control during fallow is typically accomplished through a combination of tillage and herbicides. Herbicides are the dominant tool in no-till systems, and most fallow fields receive multiple herbicide applications (glyphosate-based tank mixtures) per year for weed control. Growing cover crops during the fallow period could help suppress weeds by direct competition for light, water, and nutrients, as well as help eliminate the need for some herbicide applications or tillage.

11. How do I manage cover crops in moisture-limited regions? (cont.)

Several opportunities exist for greater cover crop adoption in this semi-arid west. However, as several researchers in the Great Plains states and further west explain, acceptance will require financial incentives that could help offset the cost of implementation plus the potential negative impacts on cash crop yield. Financial incentives could come from on-farm ecosystem services that should improve cash crop yield over time such as improved soil health, better pest management and nutrient retention or supply. Federal or state conservation programs could subsidize practices that directly reduce soil erosion, improve habitat for wildlife or provide other qualifying environmental benefits. Immediate direct income incentives could include using cover crops for livestock forage by grazing or haying or even for seed or grain during more productive years.

Cattle grazing a cover crop (left) and a pulse cover crop in wheat fallow (right), both in Montana. (Photo credits: USDA NRCS, Montana)

A number of questions arise about potential incentives for cover crop adoption in moisture limited environments and requires more investinvestigation. For example:

- How can cover crops impact problem weeds and other ecosystem services?
- What cover crop species are best and how should they be managed?
- How does grazing, haying or even grain or seed production fit?
- Can growers adopt some form of flex-fallow similar to recommendations coming from western Kansas and grow cover crops based on future moisture predictions?

Future research should focus on integration of cover crops to replace portions of the fallow period to provide additional integrated weed management along with the other benefits that come with increased diversification.

12. Do cover crops make economic sense for weed control?

Cover crops can deliver positive returns in several situations and the potential benefit to weed management is one of them. High residue weed suppressive mulches like cereal rye are perhaps most likely to provide immediate cost savings. SARE's technical bulletin on **Cover Crops Economics** states that including cover crops like cereal rye to suppress weeds could allow for one less POST herbicide application along with allowing lower cost residual herbicides (https://www.sare.org/resources/cover-crop-economics/). According to their review, in the case of severe herbicide-resistant weed infestations that could decrease yield, the weed suppression benefit from the cover crop will help off-set cover crop seed and establishment costs in the first year for soybean and by the second year for corn.

Other situations where cover crops can quickly pay include their use as livestock forage. Some cover crop advocates contend that if the crop is partially harvested from the field, it is no longer a cover crop. However, livestock grazing of cover crops can provide financial, environmental, and ecological benefits such as further recycling nutrients back into the soil, as well as managing herbicide-resistant weeds. Participation in federal and state incentive programs can also immediately help pay for their cost. Other near-term benefits can come when converting from tillage-based agriculture to no-till. Adding cover crops to the rotation can help "jump start" no-till by supplying or sequestering N, building organic matter and improving soil structure and water infiltration. Cover crops can also provide a benefit during a mid- and late-summer drought by mulching the soil and reducing evaporation or when excessive moisture conditions exist in the early season, by consuming soil moisture. Some cover crops can also immediately help with compaction issues.

The **SARE technical bulletin** on cover crop economics states that by year five, cover crop adoption should be producing a modest profit due to a combination of yield increases and lower production costs: https://www.sare.org/resources/cover-crop-economics/. These authors also believe that cover crops are a form of risk management. They believe that improving soil health will help reduce future risk from weather extremes. The bottom line is that cover crops should be valued for their short-term benefits, but also as an investment in the long-term success of the farm. Several other publications and tools are available to help guide you through the economics of using cover crops.

- Penn State article summarizing the Crops & Soils Magazine article of the American Society of Agronomy titled **Economics of Cover Crops** by Dr. Humberto Blanco, University of Nebraska: https://extension.psu.edu/economics-of-cover-crops

- Iowa State University ag economists publish **a decision tool titled Economics of Cover Crops** that allows users to input their own values in a cover crop budget. The tool includes the economic cost and benefits with and without grazing or harvesting: https://www.extension.iastate.edu/agdm/crops/html/a1-91.html

Precision Sustainable Agriculture, a public-private partnership that connects farmers with site-specific knowledge to help make better real-time decisions, has **The Cover Crop Decision Support Tool** to help users better understand the impact of incorporating cover crop species or mixtures into their farm: https://covercrop-econ.org/

13. Chart of cover crop characteristics for weed suppression.

● EXCELLENT ◕ GOOD ◑ FAIR ○ POOR

Cover Crop Species	Cover Crop Group	Competition from Living Cover	Suppression from Dead Mulch	Mix with:	Benefits	Limitations
WINTER OR SUMMER COVER CROPS						
Cereal Rye	annual grass	◕	●	legumes, other small grains, brassicas	Quick establishment, high biomass, prevents erosion, cold tolerant, N-scavenger, weed suppression, can be used as haylage	Requires timely control, N tie-up, feral rye a threat in other winter grains
Barley/ Wheat	annual grass	◑	◕	annual ryegrass, legumes, other small grains	Quick establishment, medium biomass, prevent erosion, cold tolerant, N-scavenger, weed suppression, grazing or haylage	N tie-up, not as weed suppressive as rye, matures later than cereal rye
Oats	annual grass	◕	◑	legumes, small grains, brassicas	Quick establishment, high biomass, winterkills in the North, smother crop or nurse crop, weed suppression	N tie-up, winterkills in the North
Black oats	annual grass	◕	◑	legumes, small grains, brassicas	Quick establishment, biomass greater than oats, weed suppression, winterkills in the North	N tie-up, winterkills in the North
Triticale	annual grass	◕	●	legumes, other small grains	Quick establishment, high biomass, prevents erosion, N-scavenger, cold tolerant, weed suppression, grazing	N tie-up, seed more expensive than rye or wheat, matures later than cereal rye
Annual ryegrass	annual grass	◕	○	other grasses, legumes, brassicas	Winter hardy, prevents erosion, can interseed, good for grazing	Relatively low biomass, herbicide-resistant biotypes, some tolerance to glyphosate
Hairy vetch	annual legume	◕	◕	small grains, other legumes, buckwheat	N source, winter hardy, complements small grains in mix, weed suppression, green manure, pollinator-friendly	Slow to establish, hard seed can volunteer, weed problem in small grains
Crimson clover	annual legume	◑	◑	rye, other small grains, annual ryegrass, other legumes	N source, winter hardy, good in mixes, soil builder, grazing, green manure, glyphosate-susceptible, pollinator-friendly	Slow to establish, less weed suppressive than vetch
Medium red clover	biennial legume	◕	◑	small grains, annual ryegrass	N source, winter hardy, can frost seed, hay crop, grazing, green manure, pollinator-friendly	Slow to establish, must seed early for winter survival, 2-year+ lifecycle
Yellow sweetclover	biennial legume	◑	◑	small grains, red clover	N source, soil builder and subsoil aerator, pollinator-friendly	Slow to establish, can self-seed and become a weed
Balansa clover	annual legume	◑	◑	oats, annual ryegrass, small grains	N source, green manure, winter or summer cover crop, biomass surpasses other clovers, tolerates wet and dry conditions, grazing or hay, pollinator-friendly	Limited published data
Berseem clover	annual legume	◑	◑	oats, annual ryegrass, small grains	N source, green manure, forage, tolerates drought, grazing or hay, pollinator-friendly	Not winter hardy except in the South
White or ladino clover	perennial legume	◑	○	annual ryegrass, red clover, perennial grasses	N source, long-lived perennial, living mulch, drought-tolerant, grazing, pollinator-friendly	Long-lived perennial, hard seed, mostly suitable for perennial cropping systems, herbicide-tolerant
Field pea (winter and summer types)	annual legume	◑	○	small grains	N source, quick establishment, good in mixes, low water use, hay or seed harvest, pollinator-friendly	Residues quickly degrade, winter types exist, but winter survival only in some areas
Radish (forage, oilseed, Daikon, tillage)	annual/biennial brassica	●	○	other brassicas, small grains, annual ryegrass, crimson clover	Quick establishment, winterkills in the North, can seed in late summer, large taproot relieves compaction, N-scavenger, weed suppression	Residues quickly degrade, aggressive in mixes, needs N, will flower if seeded in spring
Rapeseed (winter and spring types)	annual brassica	◕	◑	other brassicas, small grains, annual ryegrass, crimson clover	Quick establishment, soil fumigant, N-scavenger, pollinator-friendly	Residues quickly degrade, glyphosate-tolerant
Sorghum-sudangrass / sudangrass	annual grass	●	◑	buckwheat, sunn hemp, soybeans, cowpeas	Quick establishment, high biomass, soil builder, prevents erosion, N-scavenger, weed suppression, grazing or hay	Heat-loving, can produce prussic acid (poisonous to some livestock)
SUMMER COVER CROPS						
Buckwheat	annual forb	◕	○	sorghum - sudangrass, sunn hemp	Quick establishment, short lifecycle, weed suppression, pollinator and other beneficial insects	Residues quickly degrade, can self-seed
Japanese millet	annual grass	●	○	legumes and brassicas	Quick establishment, N-scavenger, weed suppression, grazing or hay	Heat-loving, needs moisture
Cowpea (black-eyed peas)	annual legume	◕	○	sorghum - sudangrass, other grasses, sunn hemp	N source, companion crop, beneficial insects, weed suppression, forage and seed	Heat-loving, needs moisture
Soybean	annual legume	◑	○	oats, sorghum - sudangrass, other grasses, sunn hemp	N source, high biomass, drought-tolerant, grazing, pollinator-friendly	Needs moisture, some disease pests, must fit in rotation
Sunn hemp	annual legume	●	○	oats, sorghum sudangrass, buckwheat	N source, high biomass, drought-tolerant, grazing, pollinator-friendly	Heat-loving, fibrous stems make no-till difficult, seeds can be toxic to non-ruminants
Sunflower	annual forb	◑	○	sorghum sudangrass, sunn hemp, cowpea, soybean	Good in mixes, compaction relief, N-scavenger, high biomass, drought-tolerant, pollinator and beneficial insects	Leaves quickly degrade, several potential insect and disease pests
Mustard spp. (e.g. white or yellow)	annual brassica	◕	○	oats, annual ryegrass, legumes, brassicas	Quick establishment, aggressive with weeds, can have short lifecycle, N-scavenger, soil fumigant, pollinator-friendly	Residues quickly degrade, can harbor flea beetles

(Chart credit: William Curran, Penn State University emeritus, based on SARE publication Managing Cover Crops Profitably: https://www.sare.org/wp-content/uploads/Managing-Cover-Crops-Profitably.pdf; graphic credit: Emily Unglesbee, GROW)

Authors, Citations and Resources

Authors
William Curran, Penn State University (emertitus)
Victoria Ackroyd, University of Maryland
Claudio Rubione, GROW
Kara Pittman, (then) Virginia Tech
Emily Unglesbee, GROW

Reviewer
John Wallace, Penn State University

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