Core Ideas:

1. Weed control with banded herbicide and cultivation was less effective than broadcast herbicides.
2. With banded herbicide plus cultivation, weed biomass increased in row crops across years.
3. Even with more weeds, crop yield and net difference in economic returns were similar between systems.
4. In the perennial forage, weed biomass and crop yield were similar between systems.
5. Weeds were consistently low in the second-year forage regardless of management.

Integrated Weed Management with Reduced Herbicides in a No-till Dairy Rotation

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Abbreviations: IWM, integrated weed management; PRE, preemergence residual herbicide; POST, postemergence broadcast herbicide; RH, reduced herbicide weed management; SH, standard herbicide-based weed management

ABSTRACT

With over 65% of agronomic crops under no-till in Pennsylvania, herbicides are relied on for weed management. To lessen the environmental impact and selection pressure for herbicide resistance, we conducted a nine-year experiment to test herbicide reduction practices in a dairy crop rotation at Rock Springs, PA. The rotation included soybean (*Glycine max* L.) – corn (*Zea mays* L.) - 3-year alfalfa (*Medicago sativa* L.) - canola (*Brassica napus* L.). The following practices were used to reduce herbicide inputs: i. banding residual herbicides over corn and soybean rows and using high-residue inter-row cultivation; ii. seeding a small grain companion crop with alfalfa; iii. plowing once in six years to terminate the perennial forage. These practices were compared with standard herbicide-based weed management (SH) in continuous no-till. We hypothesized: i. There would be more weed biomass in the reduced herbicide treatment (RH), ii. leading to more weeds in RH over time, but iii. the added weed pressure would not affect yield iv. or differences in net return. We sampled weed biomass in soybean, corn, and the first two forage years. In corn and soybean, weed biomass was often greater in RH than SH and increased over the years in the RH treatments. In the forage, weed biomass did not always differ between treatments. Yield and differences in net return were similar in most crops and years. Results

suggest that weed management with reduced herbicide inputs supplemented with an integrated approach can be effective but may lead to more weeds over time.

INTRODUCTION

Herbicide use, especially glyphosate, increased in soybean after the introduction of glyphosate-tolerant crops in 1996 (Livingston et al., 2015). Glyphosate reliance is expected to continue with the introduction of new crops with multiple herbicide-resistance genes and as more countries gain access to herbicide-resistant technologies (Green, 2016). Herbicides have been found to increase health risks in humans (Sanborn et al., 2004) and have adverse effects on aquatic ecosystems (Hunt et al., 2017) and nearby wildlife (Freemark & Boutin, 1995). Worldwide, 263 weed species have developed resistance to at least one herbicide (Heap, 2021). Farmers have responded to this rise in herbicide-resistant weeds by using more robust and costlier herbicide programs (Livingston et al., 2015). In contrast, the agricultural industry has responded by creating more herbicide-tolerant crops. Many are concerned that these solutions will continue to increase herbicide use and result in more herbicide-resistant weeds (Bonny, 2016; Heap, 2014; Mortensen et al., 2012).

Researchers have been looking for more effective and efficient ways to reduce herbicide use. In row crops, spraying herbicides only over the crop row or "banding" has proven to reduce herbicide pollution to aquatic systems (Hansen et al., 2001), but with inconsistent effectiveness in controlling weeds (Hartzler et al., 1993; Mt Pleasant et al., 1994), most likely due to the lack of between-row weed management strategies (Moomaw & Robison, 1973). Using interrow cultivation after banding herbicides has also resulted in inconsistent weed control. Some studies have found this combination to be similar to a broadcast herbicide application (Davis et al., 2012; Gómez et al., 2013; Hooker et al., 1997; Liebman et al., 2008), whereas others reported that a broadcast herbicide application was more effective for weed control (Moomaw & Robison, 1973; Snyder et al., 2016). The inconsistency of cultivation is mostly attributed to reduced effectiveness due to wet weather and wet soil conditions (Cavigelli et al., 2008; Posner et al., 2008). Finally, in perennial forage crops, annual companion crops can be added at the time of establishment to reduce weed competition and the need for chemical weed control (Liebman et al., 2008; Sheaffer et al., 2014; Spandl et al., 1999).

A crop rotation including both annual and perennial crops and diversified weed management can reduce selection pressure for a particular community of weeds and help provide weed control (Liebman and Dyck 1993). A number of studies have found that longer rotations that included perennials along with integrated weed management (IWM) techniques such as banding herbicides over the crop row, using companion crops, or replacing herbicides with tillage (Cavigelli et al., 2008; Davis et al., 2012; Gómez et al., 2013; Posner et al., 2008) provided similar weed control to herbicide-based two-year summer annual crop rotations. However, the adoption of long-term no-till management reduces the opportunity for some IWM tactics and increases reliance on herbicides due to the loss of mechanical weed control as an integrated option.

The Pennsylvania State University Dairy Cropping System Project began in 2010 to evaluate the effectiveness of several novel management practices on a simulated typical Pennsylvania dairy farm with a 65-cow herd and 97-ha of cropland. The experiment was conducted at 1/20th the scale of the simulated farm to evaluate several practices to reduce environmental impacts compared to more standard dairy-farm practices. One objective of the project was to test IWM methods that reduced herbicide and tillage inputs on the dairy, grain, feed and forage production farm. We hypothesized that compared with relying on herbicides for weed control in no-till, reducing herbicide inputs and relying on cultural and mechanical weed control would: i. increase weed dry matter (biomass) and ii. result in greater weed biomass over time, but iii. not affect cash crop yield iv. or differences in net return. The first three years indicated weed biomass increased in the row crops with reduced herbicide (RH) management compared with the standard herbicide (SH) regime, but weed biomass did not reduce crop yields (Snyder et al., 2016). We continued to test IWM vs. an herbicide-based strategy for a total of nine years. This paper will summarize the results from the first three years as a reference, but mostly focus on the last six years and summarize the weed control and crop performance results over the length of the experiment.

MATERIALS AND METHODS

The Pennsylvania State University Sustainable Dairy Cropping Systems Project was established in 2010 at the Pennsylvania State University Russell E. Larson Agricultural Research Station in Pennsylvania Furnace, PA (40.72°N, 77.92°W). Pennsylvania Furnace has a warm summer continental climate or "Dfb" Köppen Climate subtype (Arnfield, 2020). Prior to initiation of the study, the fields had been managed with no-till using conventional herbicides in a mostly corn-soybean rotation. The study was conducted using a randomized complete block design with crops as the main plot and weed management strategies as split-plots. Each crop (soybean [*Glycine max* L.] - corn [*Zea mays* L.] - 3-year forage as alfalfa [*Medicago sativa* L.] or alfalfa and orchardgrass [*Dactylis glomerata* L.] - canola [*Brassica napus* L.]) of the 6-year crop rotation was present every year in randomized main plots (37 by 27 m) and replicated four times. We compared weed management strategies in split-plots (18 by 27 m): standard herbicide (SH) or reduced-herbicide (RH). On the basis of the results at the end of each 3-year phase, along with input from an advisory panel of farmers, we modified the treatments slightly in Phase 2 (2013-

2015) and Phase 3 (2016-2018) and added nested split-split-plot (9 by 27 m) treatments in the corn and soybean crop entries (

Figures:

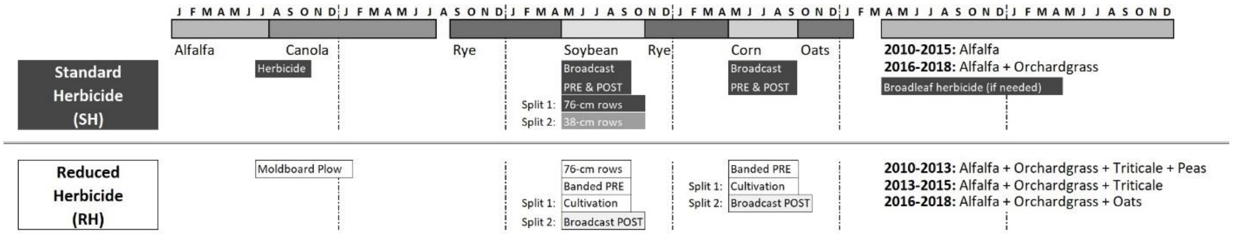


Figure 1). Weeds were sampled each year in each of the following crops: i. late summer before soybean and corn harvest, ii. at each harvest during the perennial forage establishment year (Forage Yr. 1), and iii. at the first harvest of the first forage production year (Forage Yr. 2). Weeds were not measured in the canola crop. In 2018, the soybean plots were replaced with corn to prepare for a new phase of the experiment, so only eight years of soybean results are included.

Agronomic Management

Pre-plant burndown herbicides were applied in both regimes to control weeds and/or cover crops prior to planting corn, soybean, and the perennial forage (Table 1). The SH treatment in corn and soybean included broadcast preemergence (PRE) and postemergence (POST) herbicides. In the RH treatment, PRE-herbicides were applied only to one-third of the plot area in 25-cm bands over the crop row at the time of planting, and rather than a POST herbicide application, we made one or two (weather dependent) passes with a John Deere high-residue row crop cultivator (Deere & Company, Moline, IL;

Table 2). Herbicide choice in both the SH and RH strategies was intended to provide crop rotation flexibility and reduce toxicity and potential for environmental degradation. In the RH treatment, the forage was terminated with a moldboard plow, creating one tillage event each six years. The forage in the SH treatment was terminated with a burndown herbicide application prior to seeding canola. At the start of Phase 2 in 2013, the RH treatment was split due to feedback from our advisory panel of farmers into two 9-m wide sub-plots to include banded PRE-herbicides with: broadcast POST-herbicides (RH-POST) or cultivation (RH-Cult) and both options were compared with the SH treatment (

Figures:

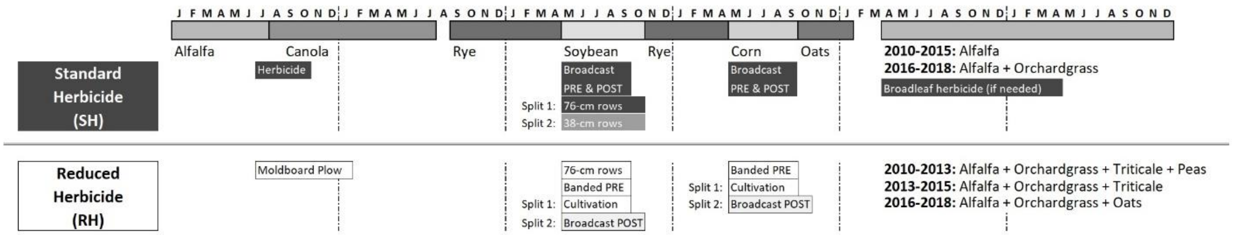


Figure 1). The RH-POST is an adaptive management option for wet springs and early summers when timely cultivation is not feasible or for growers simply not willing to introduce any tillage into the system.

Prior to starting each new phase (every three years), we evaluated the reduced herbicide strategies as well as other inputs and identified opportunities to improve them with slight modifications. These three-year phases coincided with the renewal of grant funding. Most modifications such as herbicide selection were minor and meant to improve crop tolerance and/or weed management. Other agronomic management changes included an additional split to evaluate new hypotheses (while maintaining original treatments) or small adjustments as suggested by our advisory board of farmers and researcher scientists based on their experience.

In Phase 1, corn grain was no-till planted at 79,000 seeds ha^{-1} in 76-cm rows with a John Deere 7200 planter (Deere & Company, Moline, IL). In Phases 2 and 3, corn for silage was planted at 86,500 seeds ha^{-1} instead of corn for grain to better accommodate the feed and forage diet goals of a dairy farm. In Phase 1, RH soybean were no-till planted at 494,000 seeds ha^{-1} in 76-cm rows using the John Deere planter, whereas, in the SH treatment, soybean were drilled in 19-cm rows at the same seeding rate using a Great Plains 1006NT no-till drill (Great Plains Manufacturing, Inc., Salina, KS). Slug herbivory and poor seed to soil contact due to cover crop residue interference reduced SH soybean establishment in two of three years during Phase 1

(Snyder et al., 2016).To improve populations in Phases 2 and 3 (2013-2018) and test another common soybean management technique: narrow rows, soybean were planted in either 38-cm (SH-Narrow) or 76-cm (SH-Wide) rows in nested split-split plots at the same seeding rate. Preceding both corn and soybean, 'Aroostook' rye (*Secale cereale* L; King's Agriseeds Inc., Lancaster, PA 17601) was planted as a winter cover crop at a rate of 135 kg ha^{-1}. Corn and soybean management dates and varieties are detailed in Table 2. Insecticide was only applied once in corn to control true armyworm (*Pseudaletia unipuncta*, also known as *Mythimna unipuncta*), but not in soybean, across both weed management regimes.

The SH forage included only alfalfa, whereas the RH forage included alfalfa and orchardgrass, supplemented with annual companion crop(s) during the seeding year to increase weed competition before the first forage harvest (

Table *3*). The annual companion crops in RH included triticale (*Triticosecale rimpaui* C. Yen & J.L. Yang) and pea (*Pisum sativum* L.) in Phase 1 (

Figures:

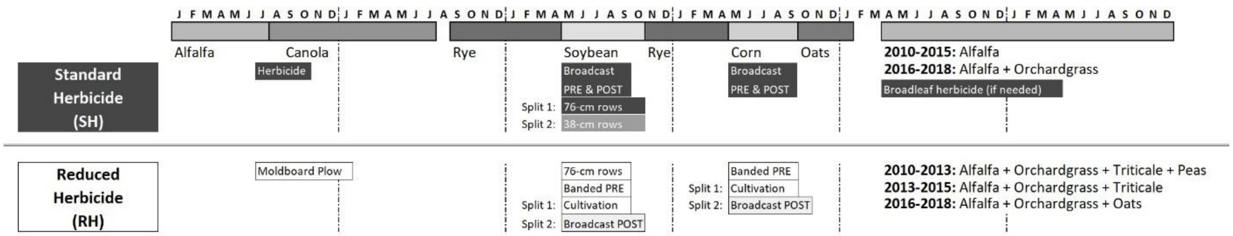


Figure 1). In 2010, the high seeding rate of the annual companion crops in RH reduced perennial forage crop establishment, so the seeding rates were reduced in the following years. However, peas continued to be too competitive with alfalfa, so in Phase 2, only triticale was included as the companion crop with alfalfa and orchardgrass. In Phase 3, we replaced triticale with oat (*Avena sativa* L.) due to seed cost and difficulties finding suitable spring triticale seed varieties. Orchardgrass was also added to the SH treatment in Phase 3 (2016-2018) based on advice from the advisory panel and to allow for better treatment comparisons. All forages were planted with the Great Plains no-till drill previously described. When weed competition was a concern in the SH treatment, we applied a postemergence (POST) herbicide to the first-year forage before the first cutting. We did not apply herbicides on second or third-year production perennial forages. In 2013 and 2015, weed competition was a concern in both SH and RH treatments during the establishment year, so both received POST herbicide applications. In both forage treatments, one or two applications of Lambda-cyhalothrin (0.05 kg ha^{-1}; Warrior II with Zeon Technology®, Syngenta Crop Protection, LLC, Greensboro, NC www.syngenta.com) were applied yearly when an economic threshold of leafhopper populations was reached as determined by damage assessments and insect counts.

Weed Biomass Sampling and Crop Harvest

In corn and soybean entries, weed biomass was sampled each year 10-15 weeks after planting (WAP) in two randomly selected 0.7 m^2 quadrats (91 by 76 cm) per split-split plot. At each harvest in the first year stands of forage and the first harvest of the second-year stand, four 0.25 m^2 (1m x 25 cm) quadrats were sampled per split-split and separated into alfalfa, orchardgrass, companion crops, and weeds. Sampled biomass was oven-dried at 60°C in a Hotpack Forced Air Oven (Hotpack, Philadelphia, PA) for a minimum of 7 days until it reached a constant weight and then weighed.

Yield for each crop was determined by harvesting one pass (strip; 27m long) down the center of each split-split. Soybean yield strips were harvested with a Massey Ferguson 550 plot combine (AGCO Corporation, Duluth, GA) and adjusted to 13% moisture. Corn grain (Phase 1) was harvested with an Almaco SPC-40 small plot combine (Almaco, Nevada, IA) and adjusted to 15.5% moisture. In contrast, corn silage (Phases 2 and 3) was harvested with a Kemper Champion 1200 Forage Harvester (Kemper GmbH & Co. KG, Stadtlohn, Germany). Perennial forage yields were collected with an MFG Chute Forage Harvester (Carter MFG. Company Inc., Brookston, IN) and adjusted to dry weight. Yields were averaged across split-split plots to create main treatment averages (unless there was a split-treatment) prior to statistical analysis.

Economic Analysis

The six-year rotation was simulated as one of two rotations to feed a 65-milking cow dairy herd using 97-ha of land in central Pennsylvania. We calculated expected feed inputs and manure outputs to include in our simulation, and our enterprise budgets reflect those assumptions. In this paper, we discuss partial budgets created for all years (2010-2018) for corn, soybean, and the perennial forage establishment year (Forage Yr. 1) and first production year (Forage Yr. 2) by phase.

Fixed ownership costs for equipment used in both weed management treatments (tractor, sprayer, no-till planter, forage drill, and forage harvester) were not included in the partial budget. Therefore, no fixed costs were included for the SH treatment as all equipment and land were also used in the RH treatment. However, in Phase 1, when SH soybean were planted with a drill and RH soybean were planted with a 76-cm row planter, the enterprise budget included equipment for soybean planting in Phase 1 (Snyder et al., 2016). Operating and ownership costs of machinery that differed between treatments (the banded sprayer, cultivation equipment, and a roller-crimper [Phase 1 only]) were calculated with the Iowa State Ag Decision Maker (Edwards, 2015) using actual receipts or estimated costs (Snyder et al., 2016).

Variable or operating costs (labor, fuel, herbicides, crop seed, and custom harvesting if necessary) were included for each treatment as these costs tended to differ. The Penn State Agronomy Guide (The Pennsylvania State University, 2019) for corresponding years was used to estimate custom harvest costs and adjusted fuel and labor costs for field operations. Seed and fertilizer prices were from actual receipts incurred, whereas herbicide costs were obtained from annual Pennsylvania state average herbicide price lists (D. Lingenfelter, personal communication, April 4, 2018). Revenue for each crop was calculated using average yields by treatment and year and average annual feed prices (V. Ishler, personal communication, May 6, 2019).

Net returns for each crop year were calculated by subtracting variable and fixed costs that differed between treatments (management specific costs) from crop revenue. Difference in net return was calculated by subtracting RH-Cult, RH-POST, or SH-Wide net returns from SH (SH-Narrow in Phases 2 and 3 soybean).

Statistical Analysis

All data were analyzed with PROC MIXED of SAS® 9.4 (SAS Institute Inc. Cary, NC). Weed biomass was transformed by taking the log of one plus the biomass to normalize the distribution. Data were analyzed with repeated measures of each plot (9-m x 27-m) by year with an autoregressive structure and the Kenward-Roger approximation (Chawla et al., 2015). Treatment, year, crop, and the interactions of these terms were fixed effects, whereas block and the interaction of block and treatment were random effects. The SLICE test was used to test our hypotheses and when there were significant interactions to conduct a partitioned F-test analysis of the LSMEANS to analyze the simple or main effects. Treatments were considered significantly different at $p<0.05$. When the split-treatments of RH-POST and SH-Narrow were included, we only compared split-treatments to RH-Cult and SH-Wide, respectively, and did not include Phase 1 in this analysis.

To lessen the effect of individual year and weather differences and minor weed management changes over the three phases on our results, we compared the weed biomass among the three phases. We replaced "year" with "phase" in the PROC MIXED model of the log-transformed weed biomass to test the hypothesis that weed biomass would increase in the RH treatment over time. We used the SLICE test when there were significant interactions to conduct a partitioned F-test analysis of the LSMEANS to analyze the simple or main effects and test if weed biomass was greater in the RH treatment in later phases of the experiment.

Because of the different scales of crop yield, yield data for each crop were analyzed separately with year, treatment, and the interactions of these terms as fixed effects, whereas block and the interaction of block and treatment were random effects. Because crops were separated and rotated among plots each year, repeated measures were not used on yield data. The Satterthwaite approximation (Satterthwaite, 1946) was used in place of the Kenward-Roger approximation.

Total annual forage harvest was summed and analyzed for perennial forage crop yields and annual weed biomass. A statistical test showed 2010 to be an outlier year for the forage establishment year, most likely due to the high annual companion crop seeding rate previously explained, so data for 2010 were removed from the statistical analysis of the forage crops.

The difference in net return for each treatment was analyzed by crop phase to determine significance in SAS 9.4 using Proc MIXED with treatment, phase, and crop as the fixed effects and year and year x treatment as random effects. We used 95% confidence intervals to test if the difference in net returns for each crop phase was different from zero.

RESULTS AND DISCUSSION

Rock Springs, PA is in a valley of the Allegheny mountains with a temperate climate. It averages 1041 mm of rain annually, with 583 mm usually occurring during the growing season of April through September (NOAA National Centers for Environmental Information, 2019).

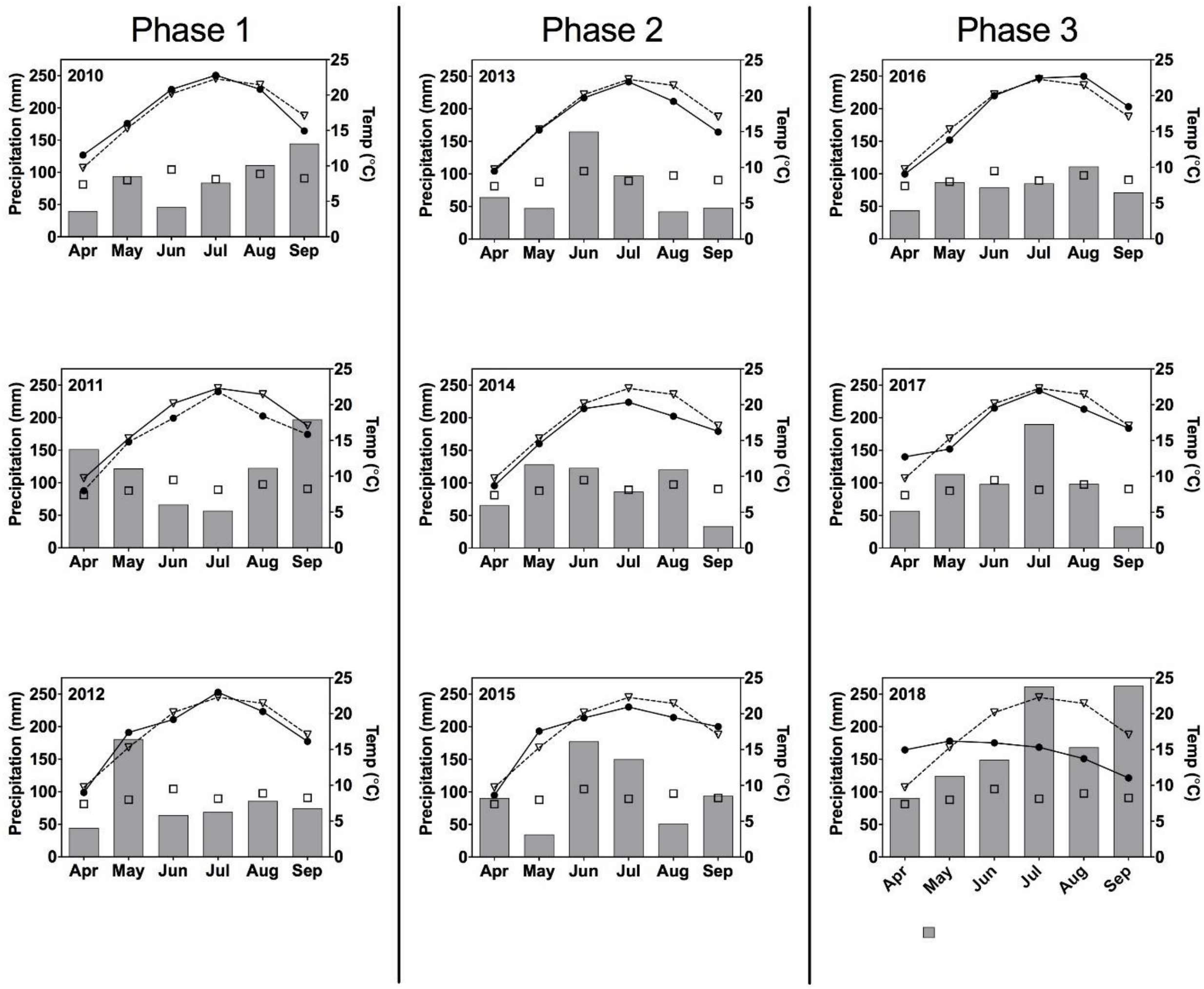


Figure 2 shows the average daily temperature and monthly precipitation for each experimental year, as well as the 30-year averages for both temperature and precipitation. Temperatures remained relatively consistent to the thirty-year average across the nine years, except that 2018 was cooler than normal. Rainfall totals were less consistent across years, with wet springs in

2011 and 2012, wet summers in 2013, 2015, and 2017, and an all-around wet growing season in 2018. Both 2012 and 2016 were drier than normal.

Weed Biomass Effects of Reducing Herbicide

The three-way interaction of year x treatment x crop was significant ($p<0.0001$). The SLICE test was used to perform a partitioned F-test analysis of the LSMEANS of the 3-way interaction for the simple effects of treatment. In most years of the row crops (six of eight years in soybean and seven of nine years in corn), the weed biomass in RH averaged 92 times larger than in SH (Figure 3). However, the weed biomass in the SH plots was consistently low, never exceeding 5 g m^{-2}. Common weed species in the row crops included mostly summer annuals. Foxtails (*Setaria spp.* L.) and pigweeds (*Amaranthus spp.* L.) were common in all three phases. Common ragweed (*Ambrosia artemisiifolia* L.) was more common in Phase 1, large crabgrass (*Digitaria sanguinalis* [L.] Scop.) and fall panicum (*Panicum dichotomiflorum* Michx.) were more common in Phase 2, and common lambsquarters (*Chenopodium album* L.) was more common in Phases 2 and 3. Dandelion (*Taraxacum officinale* F.H. Wigg.) was also a common weed in row crops and perennial forage crops.

In the forage crops, the treatments only differed in three of eight years in the forage establishment year (Forage Yr. 1) and twice in the first year of forage production (Forage Yr. 2; Figure 3). Weed biomass was greater in Forage Yr. 1 twice in RH and once in SH. In Phase 3, oats replaced the previous companion crops of triticale and peas (Phase 1) or triticale alone (Phase 2), which may have provided better weed control in RH relative to SH. Adding orchardgrass to the SH treatment in Phase 3 may also have allowed for greater weed biomass in SH caused by potential herbicide interception of the rapidly growing orchardgrass plants, coupled with heavy rain in July of 2017 and 2018 that possibly stimulated late-season weed emergence. By contrast, in Forage Yr. 2, SH had more weeds twice in eight years. Common weed species in the perennial forage crops included Canada thistle (*Cirsium arvense* L.) as well as dandelion and many of the annual grass and broadleaf weeds identified previously in the row crops (foxtails, large crabgrass, fall panicum, pigweeds, and common lambsquarters).

In Forage Yr. 1, weed biomass was 10 times larger than all other crops across the study. This could be due to weed biomass being summed across two or three individual forage harvests during Forage Yr. 1 to account for total weed biomass throughout the season, whereas weeds in row crops were harvested once at the end of the season, and only from the first forage harvest of the year in the Forage Yr. 2.

Long-term Effects

When we tested the hypothesis that weed biomass would increase in the RH treatment over the phases, the three-way interaction of phase x crop x treatment was significant ($p<0.0001$), so the SLICE test was used to determine significant treatment differences in each crop in each phase. Figure 4 shows the weed biomass of both treatments for each crop in each phase. Weed biomass in the SH treatment in corn and soybean crops was similar across the three phases. In the RH treatment, weed biomass in soybean was 11% greater in Phase 3 than Phases 1 and 2, and in corn, weed biomass was more than two and three times greater in Phases 2 and 3 than Phase 1, respectively. This indicates that our hypothesis that weed biomass would increase over years in the RH treatment was correct for the annual row crops.

In Forage Yr. 1, weed biomass in the SH treatment did not differ between Phases 1 and 2, but weed biomass in Phase 3 was almost 4 times greater than in Phase 2. By contrast, in the RH treatment weed biomass was similar between Phases 1 and 3 and was smaller in Phase 2 compared with Phases 1 and 3 by 52% (Figure 4). Because of the large weed biomass in the RH treatments in 2013 and 2015, both RH and SH received a POST application in Forage Yr. 1, which could explain why weed biomass was lower in RH these years. In Phase 3, the RH treatment contained oats and SH treatment contained orchardgrass, whereas the SH treatments in Phases 1 and 2 contained pure alfalfa. The same herbicides were used in all three phases. Oat biomass was largest in the first harvest of Forage Yr. 1 (data not shown) when weed biomass did not differ between treatments. But in the two years when RH had less weeds than SH in Forage Yr. 1 (Figure 3), there was still some oat biomass in RH in the second harvest (data not shown) when weed content was also significantly smaller than SH (197 vs. 360 kg ha^{-1} in RH and SH, respectively in 2016; 316 vs. 959 kg ha^{-1} in RH and SH, respectively in 2017). This suggests that the oats provided weed control in the first two harvests in RH. Orchardgrass may also have reduced weed control, possibly due to early growth and herbicide interception by orchardgrass plants or reduced weed competition relative to alfalfa later in the season. Alfalfa seeding rates were reduced by 45% in Phase 3 to accommodate adding orchardgrass (Table 3). Pure alfalfa may be better for weed control than an alfalfa-grass mixture. Weeds in the forage crops did not go to seed due to mowing frequency, so we believe emerged weeds in these crops did not contribute to the weed seedbank.

Weed biomass in Forage Yr. 2 was 100% smaller in Phase 3 of SH compared to Phases 1 and 2. The RH treatment of Forage Yr. 2 did not have weed biomass differences across phases, confirming the weed control benefits of rotating to a perennial forage. By rotating from summer annuals to perennials, the weed biomass in both treatments declined to low levels in most years of Forage Yr. 2 (Figures 3 and 4). Perennial crops can decrease weed biomass and possibly increase weed species abundance by both mechanical control with frequent harvests year-round and cultural control by including a competitive crop (Cavigelli et al., 2008; Teasdale et al., 2018). Others have also found that compared with annual crop rotations, including a perennial crop in both conventional and organic systems proved to provide similar or more effective weed control (Cavigelli et al., 2008; Davis et al., 2012; Liebman et al., 2008; Porter et al., 2003).

Split-treatments

In two of six years in corn and two of five years in soybean, weed biomass in RH-Cult averaged 15 times greater than RH-POST. The years when this occurred were 2015, 2016, and 2018, two of which were wet years with high rainfall in June (

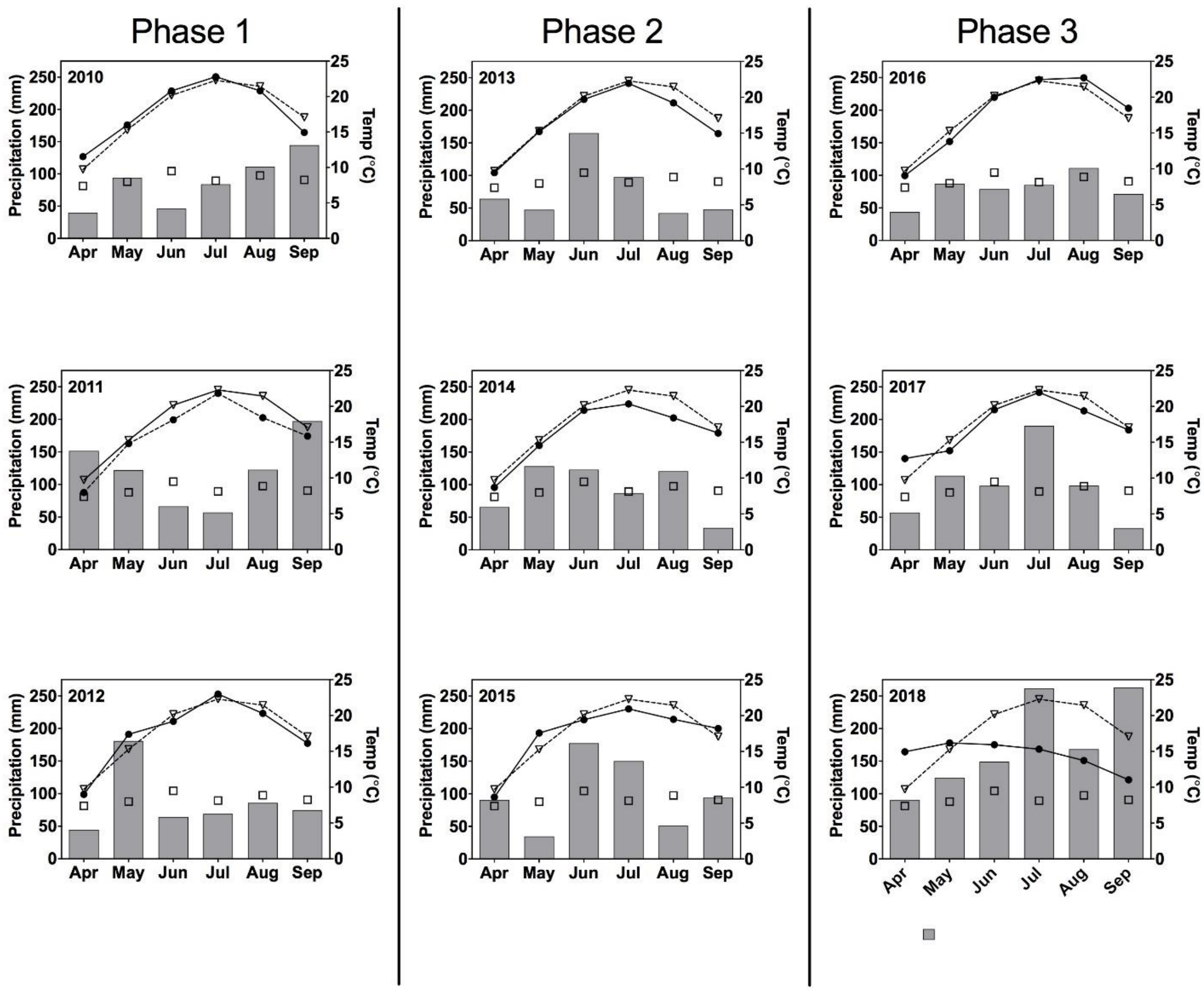


Figure 2), which likely allowed some weeds to re-establish and survive after cultivation. The effectiveness of cultivation has been found to be reduced in years with frequent rainfall or rainfall occurring soon after cultivation (Cavigelli et al., 2008; Posner et al., 2008). In contrast, weed biomass in RH-POST treatment in soybean was similar to both SH treatments except in one of five years (2017) when biomass in RH-POST was greater than SH and the same as RH-Cult (Figure 5), suggesting our adaptive management strategy was successful in most years. Weed biomass did not differ between narrow and wide row soybean in the SH treatment.

Yield and Difference in Net Returns

In five of eight years, SH soybean yielded 23% greater than RH. Yield differences in 2011 and 2012 were attributed to reduced soybean population due to slugs and cold, wet soil (Snyder et al. 2016). In 2015-2017, the narrow-row soybean yield averaged 13% greater than all other soybean treatments ($p=0.005$). However, we do not attribute this yield difference to weeds as weed biomass in the SH-Narrow and SH-Wide soybean never differed. Narrow rows can improve soybean yield by 3-12%, as reported in Iowa, Illinois, and Tennessee (Bullock et al., 1998; De Bruin & Pedersen, 2008; Walker et al., 2010), possibly due to earlier and increased canopy coverage.

Corn yields only differed between treatments once, in 2011, when RH corn yielded 6% less than SH corn ($p=0.03$). It is not clear why yields differed between treatments this year, but it is possible that larger weed biomass in RH reduced yields compared with SH.

Forage Yr. 1 yield differed between treatments in four of eight years but was not consistently greater for one treatment. In 2011 and 2012, RH yield averaged 26% greater than SH ($p<0.01$) most likely due to the large biomass of annual peas and triticale that averaged 97% of the total biomass in the first harvest of 2011-2012, when RH alfalfa averaged only 8 g m^{-2} in the first harvest, whereas SH alfalfa averaged 101 g m^{-2}. This shows the potential yield benefits of adding annual companion crop(s) (Curran, Kephart, & Twidwell, 1993; Hall, Curran, Werner, & Marshall, 1995; Ringselle, Prieto-Ruiz, Andersson, Aronsson, & Bergkvist, 2017; Sheaffer, Barnes, & Marten, 1988; Sheaffer et al., 2014). However, this is not the case for all companion crops, as we observed a yield decrease when triticale was added in 2013 and 2014 and no yield effect in 2015-2018, suggesting that the annual(s) chosen for the companion crop has a large effect on the possibility of a yield increase. From 2013-2014, RH yielded 32% less on average than SH ($p<0.001$). In the first cutting, triticale averaged 64% of total biomass (data not shown) and RH yield averaged 28% and 21% lower than SH in the first and second cuttings, respectively, suggesting the perennials needed time to recover after early competition from the annual triticale. However, by the third cutting in the establishment year, RH and SH yields did not differ. Because weed biomass was similar between the treatments in those years, this suggests that weeds did not reduce yield, and instead, we can attribute yield loss to triticale competition with alfalfa.

In Forage Yr. 2, SH annual yield was larger than RH in two of eight years. In 2012, RH yield was 83% of SH yield ($p=0.004$), possibly due to early harvest of the RH forage to control potato leafhopper (*Empoasca fabae* Harris). It is possible that the annual yields in 2016 were reduced in RH due to weed competition, as that was the only year with a difference in weed biomass. However, we do not have an explanation for why weed biomass differed in 2016. Our results are similar to Hall et al. (1995), who found no differences in forage yield, weed biomass, or profitability by the second year of forage production when comparing weed management.

For most crops and phases, net return between the RH treatment and SH treatments were similar (**Error! Reference source not found.**). This suggests that farmers could vary their approaches to weed management without much economic concern. Net return differences from 0 were only observed in Phases 1 and 2 of Forage Yr. 2. This is likely due to the difference in revenue for pure alfalfa (SH - Phases 1 and 2) versus alfalfa mixed with grass (RH - all phases and SH - Phase 3).

Herbicide Input Reduction

Herbicide input reduction was calculated with the total kg ha^{-1} of active ingredient (ai) or acid equivalent (ae) applied to each crop in each year, but only PRE (residual) and POST herbicides differed between the two treatments. The same burndown herbicide was used to terminate the cover crop and other growing vegetation in both treatments. Herbicides did not differ between SH-Wide and SH-Narrow. On average across all three phases, herbicide applications were reduced: i. in soybean by 4% in the RH-POST and 32% in the RH-Cult, ii. in corn by 30% in RH-POST and 44% in RH-Cult, and iii. in Forage Yr. 1 by 37% in the RH treatment compared with the SH treatment. After the first year of forages, herbicides were not needed in either treatment.

Not only were herbicide inputs reduced in RH compared with SH, but we also rotated modes of action to reduce the selection pressure for herbicide-resistant weeds in both treatments. We used four unique modes of action in soybean and five unique modes of action in corn. Switching to a program with a less diverse assortment of herbicides might increase the selection pressure for herbicide resistance. In future studies, herbicide inputs could be further reduced in several ways. Some research suggests that a high biomass producing cover crop terminated at planting or "planted green" could reduce the need for preemergence (residual) or postemergence herbicides later in the season (Wallace et al., 2019), specifically for targeting early-emerging summer annual weeds. Using different herbicides with greater specific activity could also potentially allow for lower use rates.

This study was unique in its length of nine years to study the long-term effects of the treatments. In 4 of 5 years in soybean and 5 of 6 years in corn, RH-POST weed biomass was similar to the SH treatment, whereas RH-Cult was greater in 6 of 8 years in soybean and 7 of 9 years in corn. When soybean yield differed, it was due to population differences in 2011 and 2012 (Snyder et al., 2016) or row-spacing in 2015-2017. For corn, yield only differed in 1 of 9 years (2013), when greater weeds in the RH treatment likely contributed to the reduced yield.

The RH-POST treatment can be an adaptive management strategy in which farmers use cultivation or a POST herbicide depending on the environmental conditions each year or if a farmer is committed to continuous no-till. For example, when fields have high weed density or wet and unfavorable conditions for cultivation, farmers can instead apply a POST herbicide and still reduce their overall herbicide use, assuming they reduce herbicide inputs by banding the PRE. Rotating mid-season weed management, coupled with herbicide rotation, can reduce selection pressure for herbicide-resistant weeds. Although RH-Cult and RH-POST provided similar net returns in corn and soybean, the option to implement a POST weed management strategy vs. mechanical cultivation was financially viable in our system and likely the preferred option for many PA farmers. However, the authors recognize that non-chemical weed management approaches such as cultivation are superior to herbicides for reducing the potential for herbicide-resistant weeds and in helping to implement an effective IWM program.

We found a general trend of greater weed biomass in the RH treatment than in the SH treatment in the annual row crops, followed by only two years with greater RH weed biomass than SH in the forage establishment year. By the first year of forage production, weed biomass in all three treatments was reduced to similar, low levels ( ), suggesting that rotating to perennial forages reduced weed biomass treatment differences.

These results partially supported our hypothesis that in most years of row crops, the RH-Cult treatment had greater weed biomass than SH and RH-POST. Furthermore, weed biomass increased over time in the two annual row crops in the RH-Cult system, supporting our second hypothesis within the annual crops. However, weed biomass did not increase in the perennial forages that followed them. It is possible that adding some adaptive management strategies, such as the RH-POST treatment, occasionally could reduce weed biomass increase over time in annual row crops.

Results also partially supported our second and third hypotheses, as increased weed biomass only reduced corn yield in one of nine years. In the forage establishment years, weed biomass was greater in RH than SH in only one of the four years when annual forage yield was smaller in RH than SH, and all were in Phases 1 and 2. In Phases 1 and 2, the annual companion crops appeared more effective at reducing annual forage yield (2 of 6 years) than weed biomass. However, by Phase 3, when the perennial forage species were similar and oat was the companion crop, weed biomass was similar or greater in SH more often than RH, and forage yields did not differ.

We created a cropping system that was diverse enough to provide some non-chemical control of weeds and was also practical for Pennsylvania dairy farmers, many of whom use no-till practices. One potential limitation of this study is the feasibility of non-livestock farms to integrate a perennial crop like alfalfa into the rotation without a planned market or on-farm use. Additionally, the existing weed density at the beginning of the experiment was low. A field with greater initial weed density or more problematic weeds such as Palmer amaranth (*Amaranthus Palmeri* S. Watson) may yield different results.

Both RH treatments did include one inversion tillage event once every six years to terminate the perennial forage prior to planting canola. Although we did not measure weeds in the canola crop, tillage reduced fall slug damage to the RH canola, possibly enhancing its competitiveness with weeds compared with the SH treatment. Further, RH canola yield was greater in one year when no-till SH canola suffered more slug damage and reduced plant populations, and canola yields were similar between treatments in 6 of 7 years (Karsten et al., 2013, 2018). Preliminary soil analyses indicated that the full tillage once in six years reduced soil organic matter in the top 0-5 cm. However, four years later, in the rotation following two years of the perennial forage, soil organic matter did not differ between treatments (Karsten et al., 2020).

There is significant focus on finding a balance between sustainability and productivity, as poor weed control can cause reduced yields, herbicide-resistant weeds, and poor crop quality (Posner et al., 2008). Earlier studies have found that reducing herbicide inputs is possible, but few have considered the long-term effect in a primarily no-till system. By using a full crop entry experiment, we had multiple replications of the long-term effects and observed yearly variations caused by the environment. This study suggests that herbicide reduction is viable provided there is a diverse rotation with a broad array of control methods. Increasing crop life-cycle diversity can reduce weed outbreaks and selection pressure for herbicide-resistance weeds. Using an integrated approach, it is possible to make agriculture more sustainable and environmentally friendly without decreasing productivity.

References

Arguez, A., Durre, I., Applequist, S., Squires, M., Vose, R., Yin, X., & Bilotta, R. (2010). *NOAA's U.S. Climate Normals (1981-2010)* (p. STATE COLLEGE, PA US USC00368449). NOAA National Centers for Environmental Information. https://doi.org/DOI:10.7289/V5PN93JP

Arnfield, A. J. (2020). Köppen climate classification. In *Encyclopedia Britannica*. https://www.britannica.com/science/Koppen-climate-classification

Bonny, S. (2016). Genetically Modified Herbicide-Tolerant Crops, Weeds, and Herbicides: Overview and Impact. *Environmental Management*, *57*, 31–48. https://doi.org/10.1007/s00267-015-0589-7

Bullock, D., Khan, S., & Rayburn, A. (1998). Soybean yield response to narrow rows is largely due to enhanced early growth. *Crop Science*, *38*(4), 1011–1016. https://doi.org/10.2135/cropsci1998.0011183X003800040021x

Cavigelli, M. A., Teasdale, J. R., & Conklin, A. E. (2008). Long-term agronomic performance of organic and conventional field crops in the mid-Atlantic region. *Agronomy Journal*, *100*(3), 785–794. https://doi.org/10.2134/agronj2006.0373

Chawla, A., Maiti, T., & Sinha, S. (2015). Kenward-Roger approximation for linear mixed models with missing covariates. *Technical Report RM 704, Department of Statistics and Probability, Michigan University*, 1–38. https://www.stt.msu.edu/Links/Research_Memoranda/RM/RM_706.pdf

Curran, B. S., Kephart, K. D., & Twidwell, E. K. (1993). Oat Companion Crop Management in Alfalfa Establishment. *Agronomy Journal*, *85*, 990–1003.

Davis, A. S., Hill, J. D., Chase, C. A., Johanns, A. M., & Liebman, M. (2012). Increasing Cropping System Diversity Balances Productivity, Profitability and Environmental Health. *PLoS ONE*, *7*(10). https://doi.org/10.1371/journal.pone.0047149

De Bruin, J. L., & Pedersen, P. (2008). Effect of row spacing and seeding rate on soybean yield. *Agronomy Journal*, *100*(3), 704–710. https://doi.org/10.2134/agronj2007.0106

Edwards, W. (2015). *Estimating Farm Machinery Costs* (PM 710). Iowa State University Ag Decision Maker. https://www.extension.iastate.edu/agdm/crops/html/a3-29.html

Freemark, K., & Boutin, C. (1995). Impacts of agricultural herbicide use on terrestrial wildlife in temperate landscapes: A review with special reference to North America. *Ecosystems and Environment Agriculture and Environment*, *52*(6), 7–91.

Gómez, R., Liebman, M., Sundberg, D. N., & Chase, C. A. (2013). Comparison of crop management strategies involving crop genotype and weed management practices in conventional and more diverse cropping systems. *Renewable Agriculture and Food Systems*, *28*(3), 220–233. https://doi.org/10.1017/S1742170512000142

Green, J. M. (2016). The rise and future of glyphosate and glyphosate-resistant crops. *Pest Management Science*, *74*, 1035–1039. https://doi.org/10.1002/ps.4462

Hall, M. H., Curran, W. S., Werner, E. L., & Marshall, L. E. (1995). Evaluation of Weed Control Practices during Spring and Summer Alfalfa Establishment. *Journal of Production Agriculture*, *8*(3), 360–365.

Hansen, N. C., Moncrief, J. F., Gupta, S. C., Capel, P. D., & Olness, A. E. (2001). Herbicide Banding and Tillage System Interactions on Runoff Losses of Alachlor and Cyanazine. *Journal of Environmental Quality*, *30*, 2120–2126.

Hartzler, R. G., Kooten, B. D. Van, Stoltenberg, D. E., Hall, E. M., Fawcett, R. S., Van Kooten, B. D., & Fawcett, R. S. (1993). On-Farm Evaluation of Mechanical and Chemical Weed Management Practices in Corn (Zea mays). *Weed Technology*, *7*(4), 1001–1004. http://www.jstor.org/stable/3987889

Heap, I. (2014). Global perspective of herbicide-resistant weeds. *Pest Management Science*, *70*, 1306–1315. https://doi.org/10.1002/ps.3696

Heap, I. (2021). *The International Survey of Herbicide Resistant Weeds*. The International Survey of Herbicide Resistant Weeds. http://www.weedscience.org/

Hooker, D. C., Vyn, T. J., & Swanton, C. J. (1997). Effectiveness of Soil-Applied Herbicides with Mechanical Weed Control for Conservation Tillage Systems in Soybean. *Agronomy Journal*, *89*, 579–587.

Hunt, N. D., Hill, J. D., & Liebman, M. (2017). Reducing Freshwater Toxicity while Maintaining Weed Control, Profits, and Productivity: Effects of Increased Crop Rotation Diversity and Reduced Herbicide Usage. *Environmental Science and Technology*, *51*, 1707–1717. https://doi.org/10.1021/acs.est.6b04086

Karsten, H. D., Adams, T., Dell, C., Ishler, V., Tooker, J., Wallace, J., Beck, T., Beegle, D. B., Curran, W. S., Hoover, R., Jahanzad, E., Kleinman, P., Richard, T., Sutradhar, A., Malcolm, G. M., & White, C. (2020). *Advanced sustainable cropping systems for dairy farms in Northeast*. https://projects.sare.org/sare_project/lne16-354r/

Karsten, H. D., Malcolm, G. M., Beegle, D. B., Curran, W. S., Ishler, V., Kleinman, P., Richard, T., Schaufler, D., & Tooker, J. (2013). Evaluation of Winter and Spring Canola in Two Dairy Farm Rotations for On- Farm Tractor Fuel and Dairy Cattle Feed. *ASA, CSSA, SSSA*.

Karsten, H. D., Sutradhar, A., Borelli, K., Malcolm, G., Aschwanden, A., Beegle, D. B., Curran, W. S., Dell, C. J., Hoover, R., Ishler, V., Kleinman, P., Meinen, R., Richard, T., & Tooker., J. (2018). Advancing sustainable cropping systems for dairy in the Northeast. *National SARE UDSA Conference*.

Liebman, M., & Dyck, E. (1993). Crop Rotation and Intercropping Strategies for Weed Management. *Ecological Applications*, *3*(31), 92–122. http://www.jstor.org/stable/1941795

Liebman, M., Gibson, L. R., Sundberg, D. N., Heggenstaller, A. H., Westerman, P. R., Chase, C. A., Hartzler, R. G., Menalled, F. D., Davis, A. S., & Dixon, P. M. (2008). Agronomic and economic performance characteristics of conventional and low-external-input cropping systems in the central corn belt. *Agronomy Journal*, *100*(3), 600–610. https://doi.org/10.2134/agronj2007.0222

Livingston, M., Fernandez-Cornejo, J., Unger, J., Osteen, C., Schimmelpfennig, D., Park, T., & Lambert, D. (2015). *The Economics of Glyphosate Resistance Management in Corn and Soybean Production*. www.ers.usda.gov/publications/err-economic-research-report/err184

Moomaw, R. S., & Robison, L. R. (1973). Broadcast or Banded Atrazine plus Propachlor with Tillage Variables in Corn. *Weed Science*, *21*(2), 106–109. http://www.jstor.org/stable/4042055

Mortensen, D. A., Egan, J. F., Maxwell, B. D., Ryan, M. R., & Smith, R. G. (2012). Navigating a Critical Juncture for Sustainable Weed Management. *BioScience*, *62*(1), 75–84. https://doi.org/10.1525/bio.2012.62.1.12

Mt Pleasant, J., Burt, R. F., & Frisch, J. C. (1994). Integrating Mechanical and Chemical Weed Management in Corn (Zea mays). *Weed Technology*, *8*(2), 217–223.

NOAA National Centers for Environmental Information. (2019). *Climate at a Glance: County Time*

Series. https://www.ncdc.noaa.gov/cag/

Porter, P. M., Huggins, D. R., Perillo, C. A., Quiring, S. R., Crookston, R. K., & Porter, P. M. (2003). Organic and Other Management Strategies with Two-and Four-Year Crop Rotations in Minnesota. *Agronomy Journal*, *95*(2), 233–244.

Posner, J. L., Baldock, J. O., & Hedtcke, J. L. (2008). Organic and conventional production systems in the Wisconsin integrated cropping systems trials: I. Productivity 1990-2002. *Agronomy Journal*, *100*(2), 253–260. https://doi.org/10.2134/agronj2007.0058

Ringselle, B., Prieto-Ruiz, I., Andersson, L., Aronsson, H., & Bergkvist, G. (2017). Elymus repens biomass allocation and acquisition as affected by light and nutrient supply and companion crop competition. *Annals of Botany*, *119*, 477–485. https://doi.org/10.1093/aob/mcw228

Sanborn, M., Cole, D., Kerr, K., Vakil, C., Sanin, L. H., & Bassil, K. (2004). *Pesticides Literature Review*.

Satterthwaite, F. E. (1946). An Approximate Distribution of Estimates of Variance Components. *Biometrics Bulletin*, *2*(6), 110–114.

Sheaffer, C. C., Barnes, D. K., & Marten, G. C. (1988). Companion Crop vs. Solo Seeding: Effect on Alfalfa Seeding Year Forage and N Yields. *Journal of Production Agriculture*, *1*(3), 270–274.

Sheaffer, C. C., Martinson, K. M., Wyse, D. L., & Moncada, K. M. (2014). Companion crops for organic alfalfa establishment. *Agronomy Journal*, *106*(1), 309–314. https://doi.org/10.2134/agronj2013.0250

Snyder, E. M., Curran, W. S., Karsten, H. D., Malcolm, G. M., Duiker, S. W., & Hyde, J. A. (2016). Assessment of an Integrated Weed Management System in No-Till Soybean and Corn. *Weed Science*, *64*(4), 712–726. https://doi.org/10.1614/WS-D-16-00021.1

Spandl, E., Kells, J. J., & Hesterman, O. B. (1999). Weed Invasion in New Stands of Alfalfa Seeded with Perennial Forage Grasses and an Oat Companion Crop. *Crop Science*, *39*, 1120–1124.

Teasdale, J. R., Mirsky, S. B., & Cavigelli, M. A. (2018). Meteorological and management factors influencing weed abundance during 18 years of organic crop rotations. *Weed Science*, *66*(4), 1–8. https://doi.org/10.1017/wsc.2018.15

The Pennsylvania State University. (2019). *The Agronomy Guide* (D. D. Lingenfelter & J. Williamson (eds.)). Penn State Extension.

Walker, E. R., Mengistu, A., Bellaloui, N., Koger, C. H., Roberts, R. K., & Larson, J. A. (2010). Plant population and row-spacing effects on maturity group III soybean. *Agronomy Journal*, *102*(3), 821–826. https://doi.org/10.2134/agronj2009.0219

Wallace, J. M., Curran, W. S., & Mortensen, D. A. (2019). Cover crop effects on horseweed (Erigeron canadensis) density and size inequality at the time of herbicide exposure. *Weed Science*, *67*(3), 327–338. https://doi.org/10.1017/wsc.2019.3

Figures:

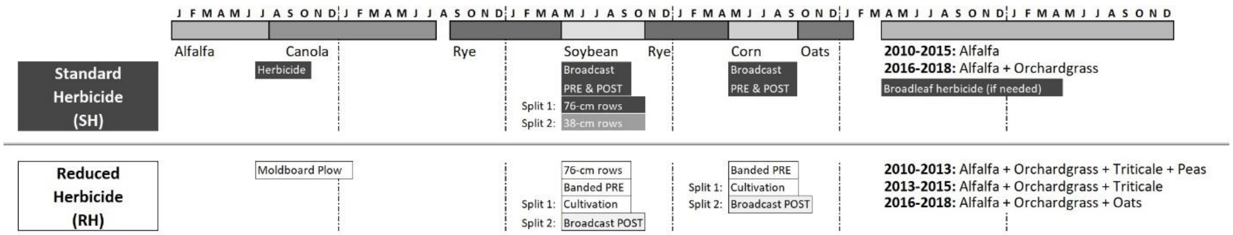


Figure 1: Six-year crop rotation with standard herbicide (SH) treatments and reduced herbicide (RH) treatments. Light gray for both treatments indicates a split of the main treatment added in 2013 (Phase 2) and continuing through 2018.

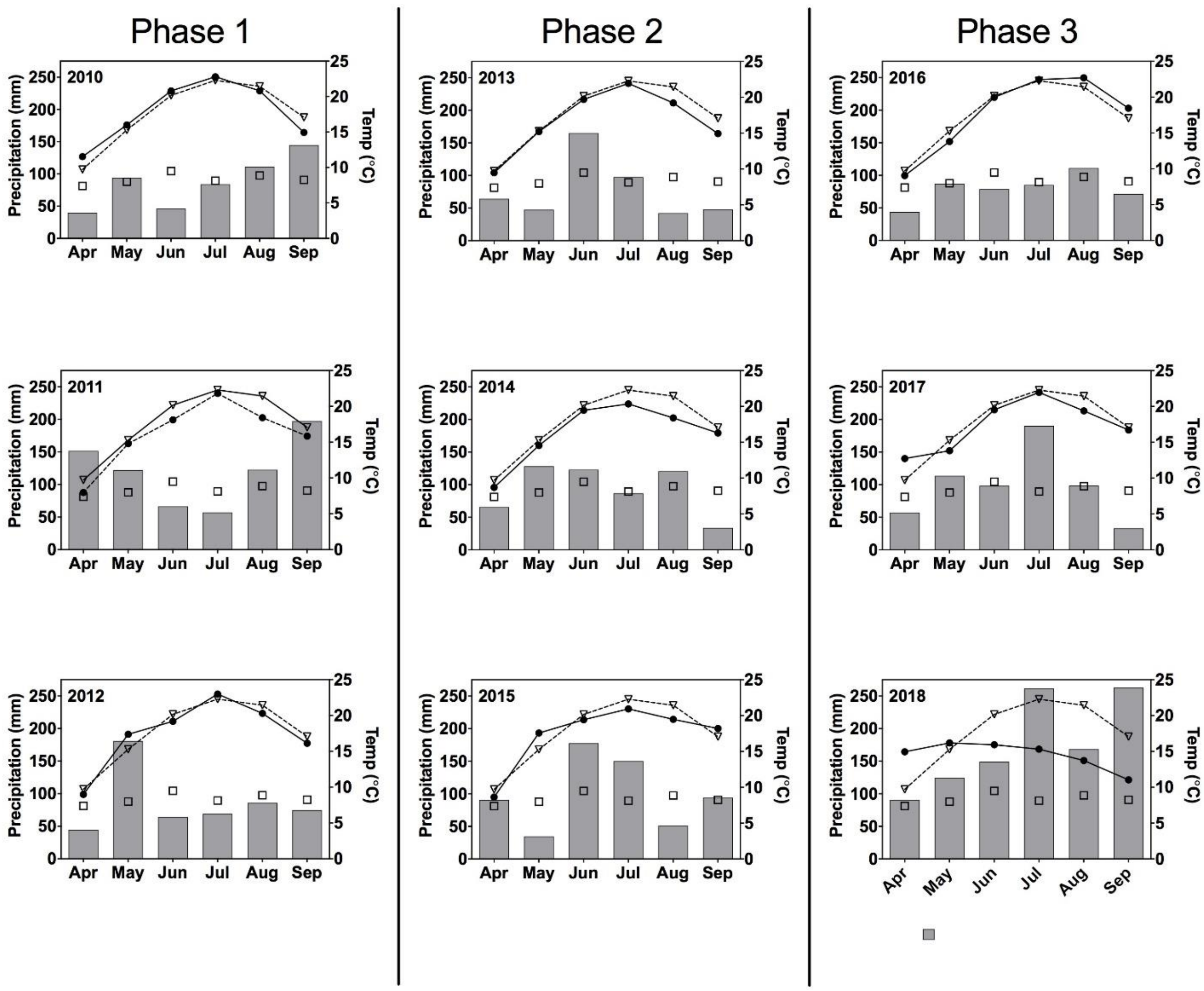


Figure 2: The average precipitation (bars) and average monthly temperature (black circles) for the summer growing season of each year. Daily temperature and precipitation obtained from USDA-ARS and USDA-NRCS weather stations near Rock Springs, PA. 30-year averages from 1981-2010 are shown for Precipitation (open squares) and Temperature (open triangles) (Arguez et al., 2010).

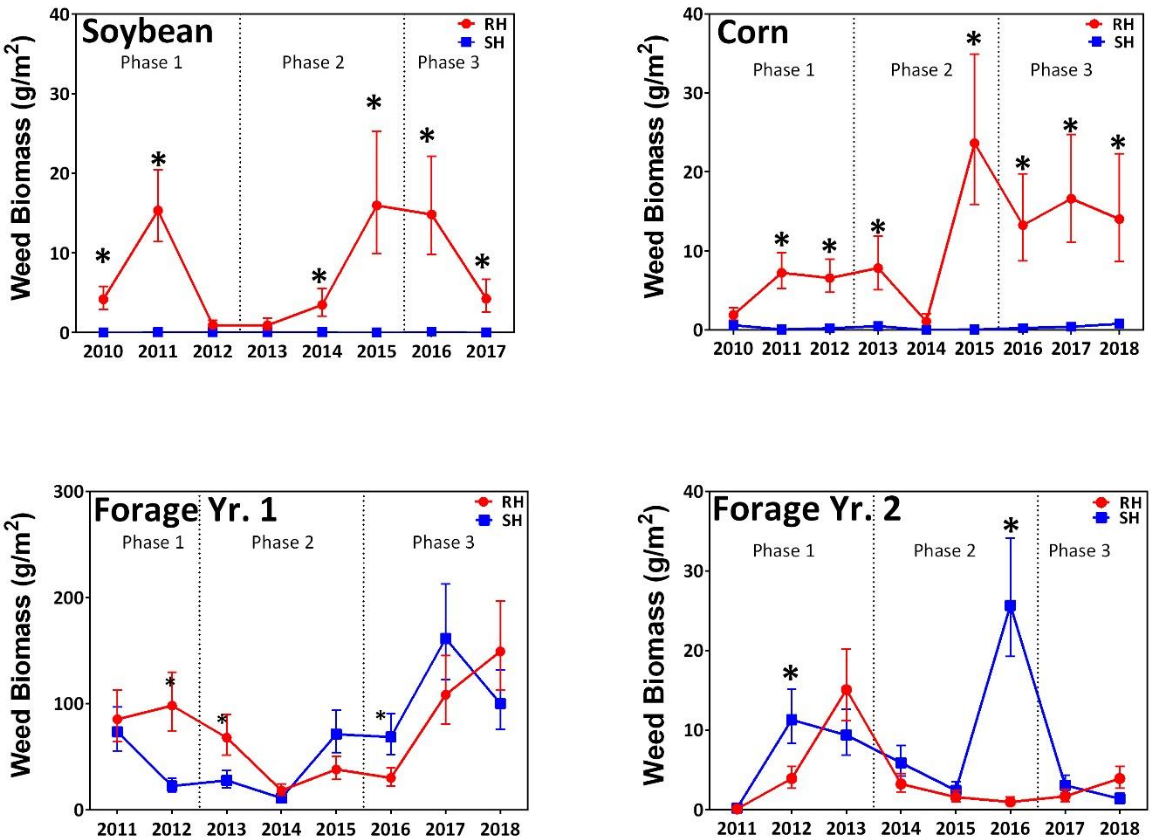
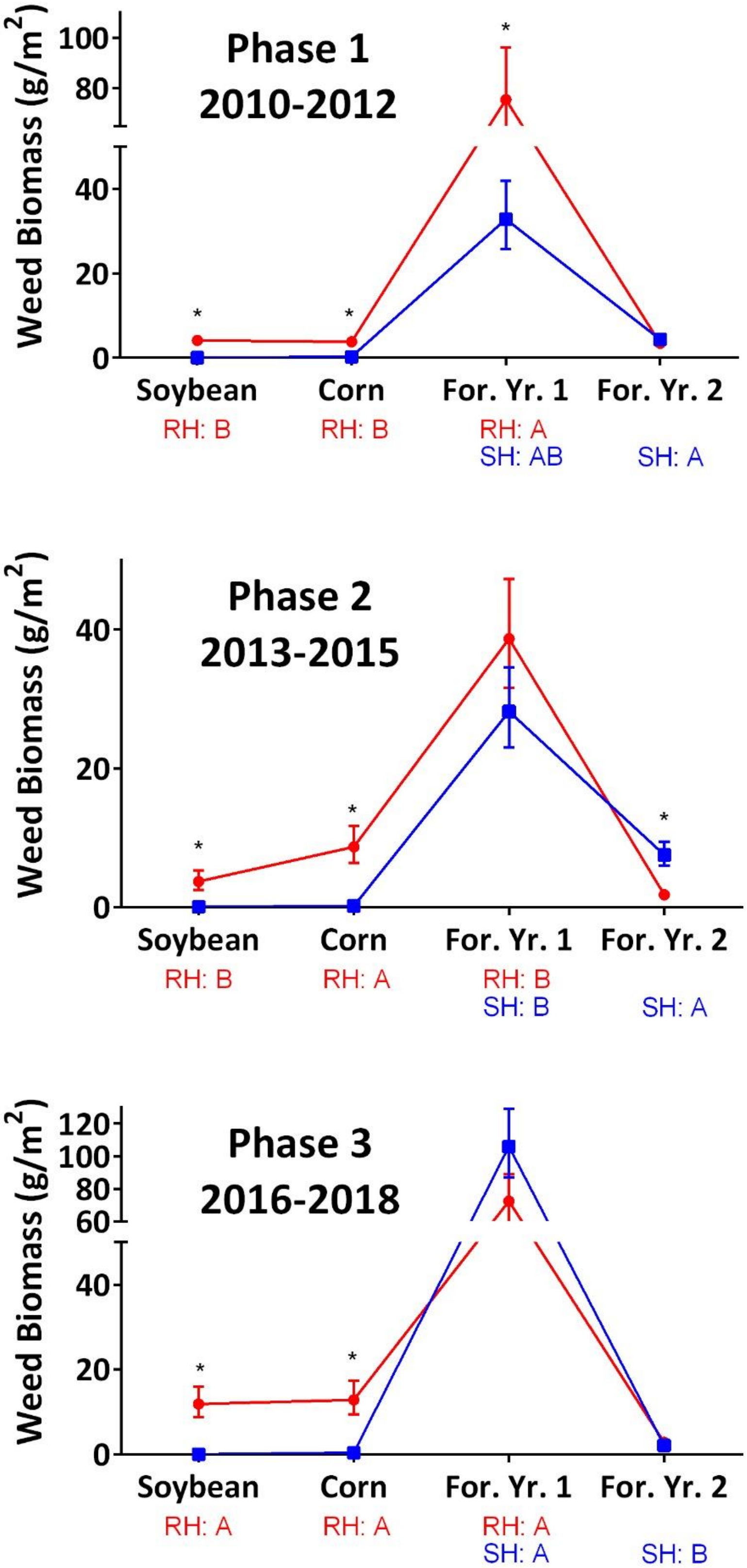


Figure 3: Weed biomass in Standard Herbicide (SH) and Reduced Herbicide (RH) treatments across Soybean, Corn, Forage Yr. 1, and Forage Yr. 2. The SLICE test was used to perform a partitioned F-test analysis of the LSMEANS of the 3-way interaction for the simple effects of treatment. Asterisks denote significant differences between treatments in a year at $p<0.05$. Weed biomass was back-transformed from the log transformation.



Phase 1
2010-2012
Weed Biomass (g/m^2)
0
20
40
80
100
*
*
*
Soybean
Corn
For. Yr. 1
For. Yr. 2
RH: B
RH: B
RH: A
SH: AB
SH: A
Phase 2
2013-2015
Weed Biomass (g/m^2)
0
20
40
*
*
*
Soybean
Corn
For. Yr. 1
For. Yr. 2
RH: B
RH: A
RH: B
SH: B
SH: A
Phase 3
2016-2018
Weed Biomass (g/m^2)
0
20
40
60
80
100
120
*
*
Soybean
Corn
For. Yr. 1
For. Yr. 2
RH: A
RH: A
RH: A
SH: A
SH: B

Figure 4: Average weed biomass of soybean, corn, establishment year of forage, and first year of forage production by phase. Reduced Herbicide (RH) is red, and standard herbicide (SH) is blue. Significant differences of simple effects were determined with the SLICE test of PROC MIXED to perform a partitioned F-test analysis of phase x crop x treatment interaction. Weed biomass was back-transformed from the log transformation.

* indicates significant differences between the RH and SH treatments at p<0.05. Different letters indicate phases that differ within the same crop and treatment at p<0.05. Soybean and Corn SH treatments and Forage Production RH treatments did not differ among phases.

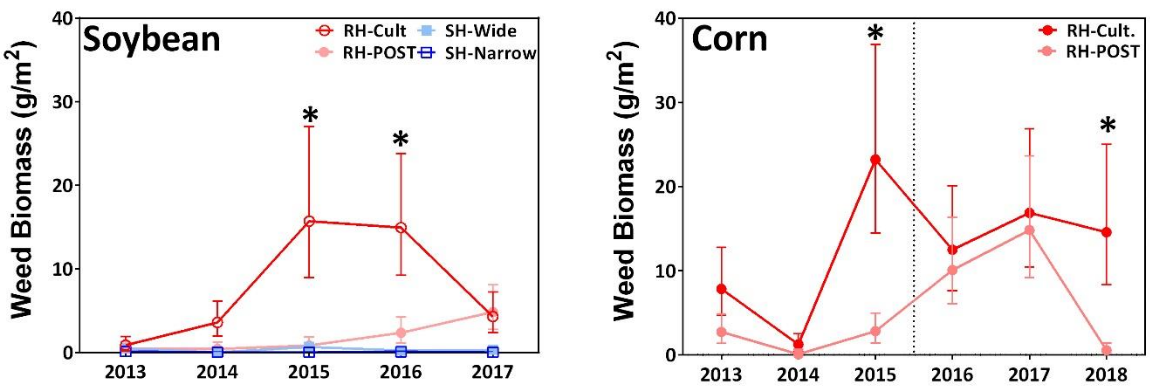


Figure 5: Split-treatment effects on weed biomass in A.) Soybean and B.) Corn. Weed biomass data were back-transformed from log transformation.

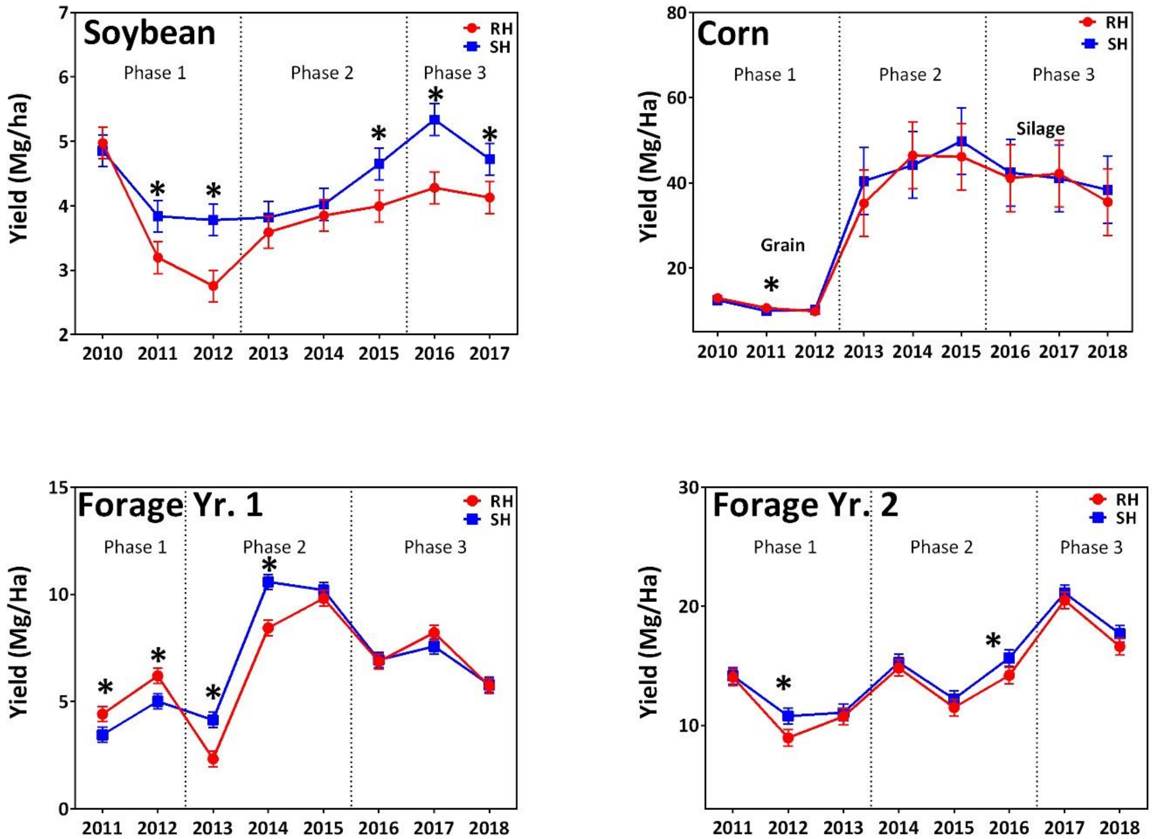


Figure 6: Yield in Standard Herbicide (SH) and Reduced Herbicide (RH) treatments across Soybean, Corn, Forage Yr. 1, and Forage Yr. 2. Asterisks denote significant differences between treatments in a year at $p<0.05$.

Tables:

Table 1: Weed control programs applied in corn, soybean, and forage establishment year by phase. Some years varied slightly. In corn and soybean, herbicides in the Standard Herbicide (SH) treatment were broadcast over the field, whereas herbicides in the Reduced Herbicide (RH) treatment were banded in 25-cm over the crop row at the same rate. RH and RH-Cult treatments had two passes with a high residue cultivator as postemergent weed control except in 2013 when RH-Cult had one pass, whereas RH-POST had a broadcast application of the SH postemergence treatment.

		Burndown		**Preemergence**		**Postemergence***		**Total**	**% of SH**
Soybean	Trt.			Kg. ai or ae ha^{-1}					
2010-2012	SH	glyphosate[1] 2,4-D[2]	0.9 0.5	flumioxazin[3] chlorimuron[3]	0.06 0.02	glyphosate	0.9	2.4	
	RH	glyphosate 2,4-D	0.9 0.5	flumioxazin chlorimuron s-metolachlor[4]	0.02 0.007 0.6			2	83%
2013-2015	SH	glyphosate 2,4-D	0.9 0.5	flumioxazin[5] pyroxasulfone[5]	0.1 0.1	glyphosate	0.9	2.5	
	RH*	glyphosate 2,4-D	0.9 0.5	flumioxazin pyroxasulfone	0.03 0.03			RH-POST: 2.4 RH-Cult: 1.5	96% 60%
2016-2017	SH	glyphosate 2,4-D	0.9 0.5	flumioxazin pyroxasulfone	0.1 0.1	glyphosate	0.9		
	RH	glyphosate 2,4-D	0.9 0.5	flumioxazin pyroxasulfone	0.03 0.03			RH-POST: 2.4 RH-Cult: 1.5	96% 60%
Corn									
2010-2012	SH	glyphosate 2,4-D	0.9 0.5	pendimethalin[6] s-metolachlor	1.6 1.8	dicamba[7] diflufenzopyr[7]	0.1 0.06	5	
	RH	glyphosate 2,4-D	0.9 0.5	pendimethalin s-metolachlor mesotrione[8]	0.53 0.6 0.035			2.6	52%
2013-2015	SH	glyphosate 2,4-D	0.9 0.5	s-metolachlor mesotrione	1.8 0.035	glyphosate dicamba diflufenzopyr	0.9 0.1 0.06	4.3	

	RH	glyphosate 2,4-D	0.9 0.5	s-metolachlor mesotrione	0.6 0.035			RH-POST: 3.2 RH-Cult: 2.5	74% 58%
2016-2018	SH	glyphosate 2,4-D	0.9 0.5	s-metolachlor mesotrione	1.8 0.035	dicamba diflufenzopyr nicosulfuron[9] rimsulfuron[9]	0.1 0.06 0.03 0.01	3.5	
	RH	glyphosate 2,4-D	0.9 0.5	s-metolachlor mesotrione	0.6 0.035			RH-POST: 2.3 RH-Cult: 2.0	66% 57%
Forage Yr. 1									
2010-2012	SH	glyphosate	0.9			2,4-DB[10]	1.1	2	
	RH	glyphosate	0.9					0.9	45%
2013-2015	SH					2,4-DB	1.1	1.1	
	RH					2,4-DB	1.1	1.1	100%
2016-2018	SH	glyphosate	0.9			2,4-DB	1.1	2	
	RH	glyphosate	0.9					0.9	45%

* Postemergence herbicides applied to corn and soybean SH treatments were also applied to RH-POST treatments at the same rates in Phases 2 and 3.
1: Roundup Powermax® Monsanto Company, St. Louis, MO www.monsanto.com; 2: 2,4-D LV4 Winfield Solutions, LLC, St. Paul, MN www.winfieldunited.com; 3: Valor® XLT Valent U.S.A. Corporation, Walnut Creek, CA www.valent.com; 4: Dual II Magnum® Syngenta Crop Protection, LLC, Greensboro, NC www.syngenta.com; 5: Fierce® Valent U.S.A. Corporation, Walnut Creek, CA www.valent.com; 6: Prowl® H2O BASF Corporation, Research Triangle Park, NC www.basf.com/us/en.html; 7: Status® BASF Corporation, Research Triangle Park, NC www.basf.com/us/en.html; 8: Callisto® Syngenta Crop Protection, LLC, Greensboro, NC www.syngenta.com; 9: Steadfast® Q DuPont, Wilmington, Delaware 19898; 10: Butyrac® 200 Albaugh, LLC Ankeny, Iowa www.dupont.com

Table 2*:* Soybean, corn, and rye cover crop management dates and varieties for Standard Herbicide (SH) and Reduced Herbicide (RH) with Cultivation (Cult) or broadcast postemergence herbicide (POST).

		Rye Cover Crop before Soybean		**Soybean**			**Rye Cover Crop before Corn**		**Corn**		
Year	Treatment	Planting	Termination	Planting	Variety	Harvest	Planting	Termination	Planting	Variety	Harvest
2010	SH RH	Nov. 1	May 19	May 27 May 25	Growmark HS2766[1]	Oct. 22	Nov. 1	Apr. 19	May 25	Pioneer 35F38[2]	Nov. 10

2011	SH RH	Sep. 22	May 6 May 12	May 20 May 31	Growmark HS2766	Oct. 25	Oct. 24	May 6 May 12	May 26	Pioneer 35F38	Nov. 10
2012	SH RH	Sep. 21	Apr. 21 May 12	May 31	Growmark HS28A12[1]	Oct. 25	Oct. 26	Apr. 21	May 1	Pioneer 35F38	Nov. 13
2013	SH - Narrow SH - Wide RH- POST RH- Cult	Sep. 24	May 3	May 21 May 20	Growmark HS28A12	Oct. 21	- Oct. 26	- Apr. 23	- May 14	- TA Seeds TA-290-08[3]	- Sep. 6
2014	SH - Narrow SH - Wide RH- POST RH- Cult	Oct. 4	May 18	June 2	Growmark HS28A12	Oct. 27	- Oct. 28	- May 18	- May 31	- TA Seeds TA-304-02[3]	- Sep. 19
2015	SH - Narrow SH - Wide RH- POST RH- Cult	Oct. 27	May 14	May 22	TA Seeds TS2849-R2S[3]	Oct. 8	- Oct. 29	- May 8	- May 15	- TA Seeds TA-089-00[3]	- Sep. 8
2016	SH - Narrow SH - Wide RH- POST RH- Cult	Sep. 24	May 4	May 25	TA Seeds TS2849-R2S	Nov. 2	- Oct. 26	- Apr. 27	- May 11	- TA Seeds TA-290-18[3]	- Sep. 16
2017	SH - Narrow SH - Wide RH- POST RH- Cult	Oct. 17	Apr. 20	May 19	TA Seeds TS2849-R2S	Oct. 27	- Nov. 10	- Apr. 20	- May 10	- TA Seeds TA-290-18	- Sep. 16
2018	SH RH- POST RH- Cult	-	-	-	-	-	Nov. 15	May 3	May 30 May 31	TA Seeds TA-477-20[3] TA Seeds TA-477-18[3]	- Oct. 1

Table 3: Forage management dates, varieties, and planting rates for Standard Herbicide (SH) and Reduced Herbicide (RH).

Year		Planting	Harvest	Alfalfa	Orchardgrass	Annuals
				Variety (kg ha^{-1})		
2010	SH	April 15	June 29, Aug. 3, Sep. 14	Genoa[1] (20)	-	-
	RH		June 29, Aug. 26	Genoa (10)	Extend (4)[2]	Pea: 40-10 (78)[3], Triticale: 718[4] (39)
2011	SH	April 22	June 20, Aug. 8, Oct. 7	Genoa (20)	-	-
	RH			Genoa (11)	Extend (4.5)	Pea: 40-10 (34), Triticale: 718 (34)
2012	SH	April 5	June 20, July 30, Sep. 6	Genoa (20)	-	-
	RH			Genoa (11)	Extend (4.5)	Pea: 40-10 (34), Triticale: 718 (34)
2013	SH	April 24	June 26, Aug. 8	Nexgrow 6422Q[5] (20)	-	-
	RH			SW420LH[6] (11)	Extend (4.5)	Triticale: 718 (34)
2014	SH	April 14	July 1, Aug. 1, Sep. 16	Nexgrow 6422Q (20)	-	-
	RH			SW420LH (11)	Extend (4.5)	Triticale: TriMark 336[4] (50)
2015	SH	April 18	June 22, Aug. 4, Sep. 17	Nexgrow 6422Q (20)	-	-
	RH			SW420LH (11)	Extend (4.5)	Triticale: TriMark 336 (50)
2016	SH	April 19	June 28, Aug. 5, Sep. 12	Nexgrow 6422Q (11)	Endurance[7] (4.5)	-
	RH			SW420LH (11)	Endurance (4.5)	Oats: EverLeaf® 126[8] (36)
2017	SH	April 17	June 29, Aug. 1, Sep. 19	Nexgrow 6422Q (11)	Extend (4.5)	-
	RH			FSG 420LH[2] (11)	Extend (4.5)	Oats: EverLeaf® 126 (36)
2018	SH	April 30	July 2, Aug. 9, Sep. 19	Nexgrow 6422Q (11)	Extend (4.5)	-
	RH			FSG 420LH (11)	Extend (4.5)	Oats: EverLeaf® 126 (36)

1: Syngenta Seeds LLC, Basel, Switzerland; 2: Farm Science Genetics® Nampa, ID 83686; 3: King's Agriseeds Inc., Lancaster, PA 17601; 4: TriCal® Superior Forage, Great Falls, MT 59405; 5: Nexgrow® Pocahontas, IA 50574; 6: Seedway, LLC, Hall, NY

14463;
7: DLF Seeds, Roskilde, Denmark; 8: ProGene Plant Research L.L.C. Othello, WA 99344

Table 4: Crop Revenue, Management Specific Costs, Net Returns, and Difference in Net Returns for Soybean, Corn, Forage Yr. 1, and Forage Yr. 2 for Standard Herbicide (SH) and Reduced Herbicide (RH) with Cultivation (Cult) or broadcast postemergence herbicide (POST) per hectare. All costs are shown on a per-hectare basis. An asterisk (*) indicates when the 95% confidence interval of the difference between the treatment and SH did not include 0. In Soybean Phases 2 and 3, SH-Narrow was used as the standard treatment.

	Soybean				**Forage Yr. 1**	
Phase 1 (2010-2012)	SH-Narrow	SH-Wide	RH-Cult	RH-POST	SH	RH
Crop Revenue[1]	$1,817		$1,546		$1,156	$1,000
Management Specific Costs[2,3]	$523		$394		$729	$726
Net Returns[2,4]	$1,294		$1,152		$427	$274
Difference in Net Returns from SH[5]			$142			$153
Phase 2 (2013-2015)						
Crop Revenue	$1,687	$1,624	$1,624	$1,624	$2,021	$1,868
Management Specific Costs	$524	$524	$536	$524	$824	$760
Net Returns	$1,163	$1,100	$1,088	$1,100	$1,197	$1,108
Difference in Net Returns from SH		$63	$75	$63		$90
Phase 3 (2016-2018)						
Crop Revenue	$1,574	$1,447	$1,447	$1,447	$1,421	$1,421
Management Specific Costs	$608	$608	$615	$650	$807	$705
Net Returns	$899	$771	$765	$730	$614	$716
Difference in Net Returns from SH		$128	$134	$169		-$102

	Corn			Forage Yr. 2		
Phase 1 (2010-2012)	SH	RH-Cult	RH-POST	SH	RH	
Crop Revenue	$2,643	$2,643		$2,383	$1,778	
Management Specific Costs	$721	$589		$708	$685	
Net Returns	$1,923	$2,054		$1,675	$1,094	
Difference in Net Returns from SH		-$131			$582	*
Phase 2 (2013-2015)						
Crop Revenue	$2,738	$2,616	$2,616	$3,316	$3,038	
Management Specific Costs	$1,438	$1,385	$1,388	$666	$617	
Net Returns	$1,300	$1,230	$1,228	$2,651	$2,420	
Difference in Net Returns from SH		$70	$72		$230	*
Phase 3 (2016-2018)						
Crop Revenue	$2,025	$2,025	$2,042	$3,697	$3,590	
Management Specific Costs	$1,087	$1,014	$1,087	$657	$543	
Net Returns	$938	$1,012	$955	$3,040	$3,047	
Difference in Net Returns from SH		-$74	-$17		-$7	