The Pennsylvania State University

The Graduate School

Department of Crop and Soil Sciences

INTEGRATED MECHANICAL WEED MANAGEMENT

IN HIGH RESIDUE CROPPING SYSTEMS

A Thesis in

Agronomy

by

Ryan Timothy Bates

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

May 2010

The thesis of Ryan Timothy Bates was reviewed and approved* by the following:

William S. Curran
Professor of Weed Science
Thesis Advisor

Robert S. Gallagher
Associate Professor of Cropping Systems

Jayson K. Harper
Professor of Agricultural Economics

David M. Sylvia
Professor of Soil Microbiology
Head of the Department of Crop and Soil Sciences

*Signatures are on file in the Graduate School

ABSTRACT

The objective of this research was to evaluate the potential of select mechanical tillage implements and reduced herbicide inputs in integrated high-residue corn and soybean systems. This integrated approach attempted to reduce the negative effects from herbicides and intense inversion tillage, while providing effective economical weed control. Treatments examined a vertical coulter, a rotary harrow, a high-residue rotary hoe, and a high-residue row cultivator in combination with soil-applied broadcast, soil-applied banded, or post-emergence herbicides. Conventional no-till using herbicides and a weedy check were included for comparison and the weed seed bank was supplemented to help ensure an effective assessment. Evaluation parameters included crop population, weed density, end of season weed biomass, surface residue, grain yield, and costs.

Weed density, crop, and production year influenced the efficacy of the mechanical implements. Treatments including herbicides reduced weed density and weed biomass compared to treatments relying on mechanical control alone. The vertical coulter and rotary harrow controlled weeds similar to a herbicide burndown treatment in corn, while with the later planting date of soybean, this treatment was not as effective as a burndown herbicide. While the rotary hoe had a minimal impact on surface residue, weed densities were higher than with the soil-applied broadcast herbicide treatments. In addition, the rotary hoe did not increase weed control in banded herbicide treatments. Treatments that included banded herbicide tended to have better weed control than treatments that relied strictly on mechanical implements, but lower weed control than broadcast herbicides. Of the mechanical tools tested, the high residue cultivator was the most effective in reducing weed density and weed biomass, while maintaining crop yield. The greater reliance on mechanical implements reduced weed control cost, but tended to have higher breakeven prices due to lower yields. Overall, mechanical tillage implements alone did not provide adequate weed control, while integration with reduced herbicide inputs maintained acceptable weed control and competitive crop yields.

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LIST OF ABBREVIATIONS

1. VC/RH – vertical coulter/rotary harrow
2. KPH – Kilometers per hour
3. DAP – days after planting
4. AMBEL – common ragweed
5. CHEAL – common lambsquarters
6. SETFA – giant foxtail
7. AMARE – redroot pigweed
8. ERICA – horseweed

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ACKNOWLEDGEMENTS

The author gratefully acknowledges those who assisted with this research, namely, William Curran, Robert Gallagher, and Jayson Harper for their guidance and support through the research process and their valuable comments while writing this work. The author would also like to thank Scott Harkcom, Mark Antle, Jim Breining, and Dwight Lingenfelter for their technical support in conducting this research and Matt Ryan for his statistical advice. Additionally, the author would like to express gratitude to Justin Dillon and fellow graduate students for their support. Finally, the author must acknowledge his family for provide support and guidance over the past 26 years.

Chapter 1

Introduction to Integrated Weed Management and Weed Dynamics

Corn and soybean production systems are a major component of U.S. agriculture, being planted on 35 and 31 million hectares in 2008 with a value of $47 and $27 billion (NASS, 2009). The majority of US corn and soybean are planted in rotation with one another in the Midwest; however, a substantial number of hectares are also grown in the Northeast on mixed crop and livestock farms. Pennsylvania alone has 546,000 and 176,000 hectares of corn and soybean (NASS, 2009). Regardless of the location of production, weed control is an important issue facing producers.

Weeds compete for sunlight, water, and nutrients, which can reduce crop yields and profitability. Weed interference varies among crops and weeds, and is also influenced by the duration of competition and climatic factors. For example, pigweed (*Amaranthus* spp.) densities of less than 1 m^{-2} emerging at the same time as soybean caused a 5% reduction in grain yield, while corn yield was reduced 13-14% with 10 giant foxtail (*Setaria faberi* Herrm.) plants per meter of row (Fausey et al., 1997). Weather is an important component in weed competition and weed seed production. In corn, the percent yield loss and velvetleaf (*Abutilon theophrasti* Medius.) seed production were reported to be higher in a warm, wet year than in a dry year or cold, wet year (Cardina et al., 1995). If weeds are allowed to set seed, the amount of seeds produced can influence future populations. For example, seed production from common lambsquarters (*Chenopodium album* L.) ranged from 30,000 to 176,000 seeds per plant and was correlated to shoot biomass (Harrison, 1990). Timing of weed emergence also impacts the ability of weeds to reproduce. For example, when pigweed emerged with corn, seed production ranged from 3,500 to 32,000 seeds per meter of row, but when pigweed emerged after corn, seed production did not exceed 5,400 seeds per meter of row (Knezevic et al., 1994). In addition, dormancy in weed seeds can prolong their impact. Burnside et al. (1996) reported that common lambsquarters, velvetleaf and many other weed seeds still germinated after being buried in the soil for 17 years. Weed competition with the crop and the prolific ability to produce many seeds as well as the viability of dormant seeds necessitates consistent and reliable weed control annually.

Weed Control

Weed control techniques have changed over the years. Before the introduction of synthetic herbicides, tillage was the principal means of weed control. The discovery of 2, 4-D in the 1940's and the triazine herbicides in the late 1950's, changed weed control approaches and it became common for chemical and mechanical methods to be used in combination. More recently, herbicide-resistant crops along with greater adoption of conservation tillage and no-till systems have reduced mechanical weed control and increased reliance on herbicides.

There are a number of tillage implements available for pre-planting and post planting weed control in corn and soybean systems. Prior to planting, the moldboard plow provides weed control by burying live vegetation and incorporating weed seeds to depths deeper than they can emerge. A less aggressive option for pre-plant tillage is the chisel plow. Depending on the design and the cropping system, this tool can be classified as either reduced tillage or conservation tillage. Chisel plows disrupt and bury live vegetation as well as weed seeds, but not to the extent that occurs with the moldboard plow. Following planting, there are additional tillage tools for mechanical weed control, such as the rotary hoe and cultivator. The rotary hoe is a full-width blind cultivation tool that works before or after crop emergence and tends to require multiple passes to control weeds. The spoon like tips of the rotary hoe tines are designed to uproot weeds just prior to emergence in the white thread stage (Bowman, 1997). Weather plays an important role in the timing and effectiveness of tillage operations. Wet soil conditions prior to or following rotary hoe operations can reduce the effectiveness of this implement even when performed at the proper time for weed control (Lovely et al., 1958). In addition, the susceptibility of weeds to the rotary hoe varies among species. In general, large seeded broadleaf species, such as velvetleaf and common cocklebur (*Xanthium strumarium* L.), are controlled less effectively with the rotary hoe than smaller seeded species (Gunsolus, 1990). Mulder and Doll (1993) reported that following the chisel plow, three passes of the rotary hoe provided 78 to 93% early season weed control. In this study, the rotary hoe was more effective in the year that early season temperatures were slightly above the historical average.

After the crop and weeds exceed the size for the rotary hoe, the next and last tillage implement to be used for mechanical weed control in field crops is the inter-row cultivator. The inter-row cultivator is designed for between crop row weed control and kills weeds by burial or by uprooting weeds and leaving them exposed on the soil surface (Bowman, 1997). The cultivator is most effective on weeds up to 10 to 15 cm tall which, which tends to occur about three to five weeks after planting (Gunsolus, 1990). Systems relying on the rotary hoe and cultivator for weed control require multiple operations between planting and the last cultivation and this combination of tools can provide effective weed control (Cox et al., 1999; Mohler et al., 1997). Mechanical weed control implements such as the rotary hoe and the cultivator require knowledge and experience to make proper adjustments to maximize the effectiveness of the implement under different soil conditions.

Most types of tillage reduce surface residue cover and may affect timing of weed emergence as well as crop density. Tillage operations can be classified into categories based on the amount of residue that is maintained on the soil surface. The moldboard plow is classified as conventional tillage and involves full width inversion tillage that generally results in less than 15% residue after planting (CTIC, 2009). In contrast, reduced tillage systems generally leave 15 to 30% residue cover, whereas conservation tillage systems generally leave more than 30%. Examples of reduced tillage tools include chisel plows and some combination tools as well as multiple passes of conservation tillage implements, whereas no-till, strip till, ridge till, and mulch-till are regarded as conservation tillage systems (CTIC, 2009). Conservation tillage tools generally are more shallow tillage tools that do not incorporate plant residues. Depending on the timing and number of operations, type of surface residue, and configuration of an implement the amount of surface residue remaining varies.

Plant residues on the soil surface can influence weed management. Surface residue increased the emergence of giant foxtail by reducing evaporation and improving germination conditions (Mester and Buhler, 1991). In general, weed emergence following tillage is more rapid and the period for emergence may be shorter, while in no-till emergence is more gradual, but does depend on weather and weed species. This more rapid weed emergence following tillage is due to direct light exposure to weed seeds, increased soil temperatures and greater temperature fluctuation, and changes to the chemistry of the soil solution (Liebman et al., 2001). Buhler (1992) reported rapid weed emergence following tillage for green foxtail (*Setaria* *virdis* L.) and common lambsquarters, but found tillage did not influence the emergence of redroot pigweed. In addition, surface residue can prolong the emergence of common annual weeds by maintaining surface moisture and providing a longer period for favorable germination (Buhler et al., 1996).

Some of the differences in weed emergence can be associated with the location of the weed seed in the soil and tillage can have a significant impact on the depth weed seeds are buried. Under conventional tillage systems, weed seeds become more evenly distributed throughout the soil profile (Cardina et al., 1991; Clements et al., 1996) and as tillage decreases seeds tend to be more concentrated near the soil surface. Clements et al (1996) reported 61% of weed seeds were in the top 5-cm in a chisel plow system, while Chauhan et al. (2006) reported in a mulch-till system the majority of the seeds were at a depth of 2 to 5 cm. In no-till systems, weed seeds become concentrated near the surface with 74 to over 90% in the top 5-cm of the soil (Cardina et al., 1991; Clements et al., 1996).

Along with distribution of weed seeds in the soil, tillage can also have a significant impact on the composition of weeds that emerge. Cardina et al. (1991) reported that the number of species forming the majority of the seed bank increases as tillage was reduced. In conventional tillage systems, perennial weeds are less of an issue because they deeply bury the weed propagules and prevent or slow their emergence (Upadhyaya and Blackshaw, 2007). Weed seed size can also influence which weeds emerge in different tillage systems. Smaller seeded weeds are more adapted to germinate and establish at or near the soil surface and have the greatest potential to increase in population in conservation tillage systems (Buhler et al., 1996). In contrast, when left on the surface, the larger seeded velvetleaf germinated similar to buried seeds, but had a lower survival rate (Mester and Buhler, 1991). The flora of weeds under different tillage systems will influence weed management practices and must be considered.

Environmental concerns with tillage for weed control

Although tillage can be an effective weed control tool, it can also expose soil and result in erosion and loss of a limited resource. Soil is a vital component for productive agricultural systems and erosion by water is a major source of soil loss in agricultural landscapes. Conservation efforts by farmers have reduced soil losses over the past 20 years (NRCS, 2003). In 2007, 21 and 40% of the US corn and soybean crops were no-tilled, with an additional 18 and 22% mulch tilled (CTIC, 2009). In contrast, organic corn and soybean production which relies on intense tillage to control weeds is increasing 6.8% and 5.6% annually (NASS, 2009). Surface cover is often considered the most important soil erosion control factor that can be influenced by management (Romkens et al., 2002). Conservation tillage leaves crop residue on the surface helping to absorb the impact of falling raindrops and slowing surface runoff. In no-till systems, soil losses are lower than in conventional tillage systems due to more residue cover resulting in a higher resistance to soil particle detachment (Alberts and Neibling, 1994). Crop residue can reduce soil erosion, increase water infiltration, and decrease runoff rate and volume (Alberts and Neibling, 1994). However, some no-till soils can also be prone to crusting and sealing resulting in reduced water infiltration. If surface residue can be maintained in combination with limited tillage, infiltration rates could be increased by breaking soil crusts and increasing surface roughness while reducing the soil erosion potential.

Soil erosion has both on-site and off-site implications. The on-site impacts of soil erosion include lower crop yields due to reduction in effective rooting depth, loss of plant nutrients and soil organic carbon, and loss of productive land area (Lal, 1998). Off-site impacts include sedimentation of waterways, promotion of premature aging of lakes and estuaries, reduced recreational activities, negative effects on aquatic plant and animal life, and possibly endangering human health (Ribaudo, 1986). In addition, off-site effects of soil erosion include the impact of pesticides and nutrients that move with the soil particles and water and pollute water resources. Because herbicides are concentrated near the soil surface, such events can lead to substantial herbicide losses with surface water run-off (Shipitalo and Owens, 2006).

Reliance on Herbicide

Herbicides have been instrumental in reducing yield and economic losses from weeds. Gianessi and Reigner (2007) estimated that if tillage and hand pulling replaced herbicide use in the US, it would take 70 million laborers to maintain weed control levels and crop production would still decrease by 20% due to weed competition. In Ontario, Canada in 2004, atrazine was estimated to provide an economic benefit of $26.1 million for corn producers through lower weed control costs and better weed control (Swanton et al., 2007). It is also estimated that glyphosate and glyphosate-resistant crops have saved US farmers $1.2 billion by reducing overall herbicide use and the number of applications, tillage, and hand weeding costs (Gianessi, 2005). In the US, 97% of corn and 98% of soybean hectares are treated with herbicides annually (NASS, 2009). Some scientists believe that stronger regulation or prohibition of commonly used herbicides (e.g. atrazine) may result in an increase in the number of herbicides and applications necessary to control weeds, which may increase weed control cost and reduce profitability (Swanton et al., 2007).

Although there are many herbicide products available for both corn and soybean, most of the commonly used herbicides represent only a few chemical families and herbicide modes of action. Furthermore, the modes of action available for corn and soybean often overlap, complicating resistance management efforts (see following section). In corn and soybean, herbicide application timing can be separated into three broad categories: burndown, soil-applied residual (pre-emergence), and post-emergence. A burndown herbicide replaces pre-plant tillage and is designed to kill emerged vegetation prior to planting or before crop emergence. It typically includes a non-selective herbicide such as glyphosate (group 9) or paraquat (group 22) that may be supplemented with 2, 4-D or dicamba (group 4) to improve broadleaf control (Ross and Lembi, 2008). Mallory-Smith and Retzinger (2003) published a classification system using a numbering system for a herbicide's site of action, chemical family, and common name that is largely accepted by regulatory agencies in the US to aid in herbicide resistance management. Soil-applied residual herbicides are applied near planting before crop emergence to control weeds as they germinate for several weeks into the growing season. Common soil-applied residual herbicides include triazine (group 5), chloracetamide (group 15) and triketone (group 27) chemical families for corn and chloracteamide and triazinone (group 5) in soybean (Ross and Lembi, 2008). Post-emergence herbicides are applied to control weeds after emergence and are absorbed through the foliage. Common post emergence herbicides include triazines, sulfonylureas (group 2), glyphosate, and triketones in corn, and aryloxyphenoxypropionate and cyclohexanedione (group 1), and glyphosate in soybean (Ross and Lembi, 2008). While other herbicides are available for corn and soybean, these herbicides are commonly used and demonstrate the overlap between those available for corn and soybean as well as application timing. The development of herbicide-resistant crops has allowed for the non-selective application of herbicides such as glyphosate and glufosinate (group 10) to corn and soybean (Mallory-Smith and Retzinger, 2003). This technology has allowed for the use of similar modes of action across corn and soybean systems targeting the same or similar weed species.

With the introduction of glyphosate-resistant crops, there has been a shift in herbicide use and the reliance on fewer herbicide modes of actions. In 1994, the triazine herbicides atrazine and cyanazine were applied to 68 and 21% of the US corn crop. By 2005, cyanazine had been removed from the market and atrazine was still used on 66% of corn hectares. From 1994 to 2005, chloracteamide use in corn decreased 10% to 46% (NASS, 2009). In contrast, glyphosate was applied to only 4% of corn crop in 1994, but increased to 31% by 2005. Glyphosate use in corn continues to rise, increasing 12% since 2003 (NASS, 2009). In 1995, imazethapyr (group 2) was applied to 44% of the soybean crop and only 20% of crop received a glyphosate application in the burndown treatment (NASS, 2009). In addition, nine other herbicides were used on at least 10% of the soybean crop in 1995 representing groups 1 through 6. Glyphosate-resistant soybean was first introduced in 1996 and by 2000, 62% of the soybean crop received at least one glyphosate application and only four other herbicides (representing groups 2 and 3) were applied to at least 10% of the hectares. By 2006, 95% of the crop was treated with glyphosate with an average of 1.7 applications per hectare and other than 2, 4-D, which was applied on 7% of the hectares, no other herbicide was used on more than 5% of the soybean crop (NASS, 2009). The increased application of a select few herbicide groups increases the likelihood of developing herbicide-resistant weeds.

Herbicide Resistance

Herbicide-resistant weed communities are present where intensive use of herbicides occurs (Heap, 1997). The extensive adoption of glyphosate-resistant corn and soybean has lead to a dramatic increase in the selection pressure for glyphosate on weed communities due to its increased use (NASS, 2009). Surveys of US farmers show that many are not overly concerned with herbicide resistance, because they believe that new herbicides or technology will be introduced to control herbicide-resistant weeds (Llewellyn et al., 2002; Scott and VanGessel, 2007). However, no new herbicide modes of action have been released into the marketplace for several years (Johnson et al., 2009). In contrast to the opinion of some Midwest farmers, Scott and VanGessel (2007) reported that famers in the Mid-Atlantic region managing glyphosate-resistant horseweed thought it was important to preserve glyphosate for future use even if it cost more to manage weeds today. In no-till systems, chemical weed management tactics that are effective at delaying herbicide-resistant weeds relies on rotating herbicide modes of action within and between years and tank-mixing effective multiple modes of action. Although this approach can be effective in both the control and delay of resistant weeds, herbicide-based weed management will continue to exert selection pressure for resistance (Gressel and Segel, 1990; Jasieniuk et al., 1996) and less reliance on herbicides would reduce the potential for herbicide-resistant weeds. Both multiple and cross resistance have been identified in many of the more common herbicide-resistant weeds. If weeds evolve resistance to multiple modes of action as is the case for glyphosate and ALS-resistant horseweed [*Conyza canadensis (*L.)Conq.] , common ragweed (*Ambrosia artemisiifolia* L.), and giant ragweed (*Ambrosia trifida* L.), the number of effective herbicides available to control them becomes fewer.

Globally, there are 341 resistant weed biotypes in 194 species (Heap, 2010). In the U.S., the first confirmed herbicide-resistant weed was spreading dayflower (*Commelina diffusa* Burm. f.) to the synthetic auxin herbicides in 1957 (Heap, 2010). The number of herbicide-resistant weed biotypes increased to 46 by 1996, with 130 being reported today (Heap, 2010). Resistance to the triazine (group 5) and acetolate synthesis (ALS) inhibitor (group 2) herbicides are the most prevalent in the United States, with 24 and 43 herbicide-resistant weed biotypes, respectively (Heap, 2010). Glyphosate has been used for over 30 years, but it was not until rapid adoption of glyphosate-resistant soybean and corn systems that glyphosate-resistant weeds evolved (Heap, 2010). The first confirmed case of glyphosate resistance was discovered in horseweed in 2000 (VanGessel, 2001). In addition to horseweed, common ragweed, giant ragweed, palmer amaranth (*Amaranthus palmeri* S. Wats), common waterhemp (*Amaranthus rudis* Sauer), Italian ryegrass (*Lolium multiflorum* Lam.), kochia [*Kochia scoparia* (L.) Schrad.], and johnsongrass [*Sorghum halepense* (L.) Pers] have confirmed cases of glyphosate resistance in corn and/or soybean systems (Heap, 2010). The increasing adoption of glyphosate-resistant crops will help further the development for glyphosate-resistant weeds.

Off-site impact of herbicides

Although herbicide resistance is a serious management concern for farmers, there are other off-site issues associated with herbicides that have caused their use to undergo regulatory scrutiny. Residual herbicide chemistries, such as the triazines and chloracetamides, can have significant loss to surface runoff and leaching from agricultural land (Graymore et al., 2001; Shipitalo and Owens, 2006). Herbicide losses tend to be more related to timing of rainfall relative to the herbicide application than the total amount of water runoff (Hansen et al., 2001; Shipitalo and Owens, 2006) and application of soil-applied herbicides in corn and soybean systems occurs in the spring during frequent rainfall periods. In a recently monitoring study of US watersheds, approximately 56% of agricultural streams have one or more herbicides that surpass at least one aquatic-life level (Gilliom, 2007). An aquatic life level is surpassed when the survival and/or reproduction of aquatic organisms is negatively impacted. In this report, atrazine, metolachlor, cyanazine, alachlor, and acetochlor, were detected most often and their concentrations were directly related to the intensity of herbicide usage (Gilliom, 2007). Another study monitoring private wells in Iowa found 70% contained herbicide compounds with 42% containing more than one herbicide active ingredient (Kolpin et al., 1997). In addition, as herbicides degrade, metabolites can still be a detected and have been found to occur as frequently or more frequently than the parent molecules (Battaglin and Goolsby, 1999). As a result of the frequent detection in water resources, atrazine was banned by the European Union because of ubiquitous and unpreventable contamination of ground and surface waters (Sass and Colangelo, 2006). Continued detection of atrazine and other herbicides in ground and surface water could cause similar actions in the United States.

The major concern for herbicide pollution in our water systems comes from the potential negative effects they can have on humans and other animals. Atrazine is one of the most controversial herbicides due to its potential impact on aquatic life (Hayes, 2004). In fish, atrazine has been shown to alter swimming behaviors by affecting sensory organs and the nervous system (Graymore et al., 2001). At concentrations common in freshwater ecosystems, atrazine was linked to trematode infections that lead to a decline in amphibian species (Rohr et al., 2008). Male frogs exposed to atrazine have developed testicular oocytes and gonad development was retarded (Hayes et al., 2002). In a review by Dearfield et al. (1999), acetochlor and alachlor increased nasal tumors in rats and metolachlor increased the incidence of liver tumors. Further research has found mixtures of herbicides can have a more severe impact than a single active ingredient. When used alone, S-metolachlor had no effect on frogs, but when combined with atrazine the negative effects of atrazine increased (Hayes et al., 2006). In humans, Garry et al. (1996) reported an increase in rate of birth defects in offspring born in high use chlorophenoxy regions of the US. Oliveira et al. (2007) reported glyphosate may have negative effects on the male reproductive tract of drakes (*Anas platyrhynchos*), while Daruich et al. (2001) found glyphosate may negatively affect the liver in pregnant rats and their fetuses. In contrast, a review by Williams et al. (2000) concluded that glyphosate does not result in adverse effects on development, reproduction, or endocrine systems in humans and other mammals. In addition, other components of the herbicide formulations such as surfactants may have negative health effects (Walsh et al., 2000). Offsite impacts of herbicides will be further scrutinized in the years to come and the benefits will be weighed against the potential negative impacts. When the negative impacts are believed to override the benefits of a herbicide, it may be removed from the marketplace.

Integrated Weed Management in Reduced Tillage Systems

Although herbicides are generally an important component for managing weeds, integrated mechanical and chemical weed control tools can help reduce reliance on herbicides, thereby reducing the threat for the evolution of herbicide-resistant weeds and off-site movement into surface and ground water systems. There is strong evidence that post plant mechanical weed control in corn and soybean systems is feasible and can reduce the amount of herbicide required to achieve acceptable levels of weed control (Buhler et al., 1995; Eadie et al., 1992; Mt. Pleasant et al., 1994; Mulder and Doll, 1993). In a chisel plow system, Mulder and Doll (1993) reported that integrating herbicide and mechanical treatments generally provided greater than 90% control of weeds. In this same study, rotary hoeing plus cultivation produced crop yields equal to the herbicide treatments. An integrated approach can reduce herbicide use by using banded herbicides in conjunction with cultivation. Mt. Pleasant et al. (1994) reported that banded herbicides, rather than broadcast, reduced herbicide use by 67% and inter-row cultivation provided adequate weed control and corn yield. In addition, on farm research has found that corn yielded the same as with broadcast herbicides with banded herbicide supplemented with cultivation (Hartzler et al., 1993). A survey in Missouri in the mid-1990's found that about 30% of farmers tried banding herbicides and 60% of these farmers continued to use this tactic (Rikoon et al., 1996).

Previous research investigating weed management in conventional and reduced tillage systems can provide useful insights, but often does not address integrated strategies in high residue systems where soil erosion is a key concern. In production systems that do not utilize primary tillage, residue management and soil conditions become important issues when thinking about mechanical weed control. For example, conventional rotary hoes and inter-row cultivators will not penetrate the soil in no-till systems and they are incompatible with the high levels of residue generally found in no-till or conservation tillage systems. Mechanical weed control implements for high residue systems need to be designed to accommodate and maintain residue, while at the same time providing effective weed control. High residue mechanical weed control implements have been developed and are commercially available, but little objective information exists to support the use of these tools. Our challenge was to evaluate high residue mechanical weed control implements for their inclusion into an integrated weed management system that reduces the potential negative impacts of both intensive herbicide use and tillage.

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Chapter 2

Integrated Mechanical Weed Management in High Residue Corn Systems

Abstract

The objective of this research was to evaluate the potential of select mechanical tillage implements and reduced herbicide inputs in integrated high residue corn systems. This integrated approach attempted to reduce the negative effects from herbicides and intense inversion tillage, while providing effective economical weed control. Treatments examined a vertical coulter, a rotary harrow, a high-residue rotary hoe, and a high-residue row cultivator in combination with soil-applied broadcast, soil-applied banded, or post-emergence herbicides. Conventional no-till using herbicides and a weedy check were included for comparison and the weed seed bank was supplemented to help ensure an effective assessment. Evaluation parameters included crop population, weed density, end of season weed biomass, surface residue, grain yield, and costs.

Weed severity and production year influenced the efficacy of the mechanical implements. Treatments including herbicides reduced weed density and weed biomass compared to treatments relying on mechanical control alone. While the vertical coulter and rotary harrow reduced residue, the combination controlled weeds similar to a herbicide burndown treatment. While the rotary hoe had a minimal impact on surface residue, weed densities were higher than with the soil-applied broadcast herbicide treatments. In addition, the rotary hoe did not increase weed control in banded herbicide treatments. Treatments that included banded herbicide tended to have better weed control than treatments that relied strictly on mechanical implements, but lower weed control than broadcast herbicides. Of the mechanical tools tested, the high residue cultivator was the most effective in reducing weed density and weed biomass, while maintaining crop yield. The greater reliance on mechanical implements reduced weed control cost, but tended to have higher breakeven prices due to lower yields. Overall, mechanical tillage implements alone did not provide adequate weed control, while integration with reduced herbicide inputs maintained acceptable weed control and competitive crop yields.

Nomenclature: Corn, *Zea mays* L.; giant foxtail, *Setaria faberi* Herrm.; common lambsquarters, *Chenopodium album* L.; redroot pigweed, *Amaranthus retroflexus* L.; horseweed *Conyza Canadensis* L.; common ragweed, *Ambrosia artemisiifolia* L.;

Key Words: integrated weed management, mechanical weed control, conservation tillage, vertical coulter, rotary harrow, high residue rotary hoe, high residue cultivator, banded herbicides

Increasing concerns over soil erosion, potential herbicide resistance (Heap, 2010) along with surface and groundwater contamination of soil-applied herbicides such as atrazine and the chloracteamides (Gilliom, 2007), as previously discussed in Chapter 1, are leading to a greater need for developing better management plans that integrate reduced herbicide use while maintaining the benefits of conservation tillage. Although herbicides are generally an important component for managing weeds in high residue systems, there are tools that can help reduce reliance on herbicides, thereby reducing the development of herbicide-resistant weeds, and off-site movement into surface and ground water systems.

High residue mechanical weed control implements have been developed and are commercially available, but little objective information exists to support the use of these tools in no-till or conservation tillage production systems. In particular, the weed control benefits of pre-plant tillage tools available for use in conservation tillage systems have not been substantiated in replicated experiments. The vertical coulter is a relatively new implement and has been used primarily as a means to increase soil temperatures in the top few centimeters of the soil prior to planting. It is equipped with a series of fluted coulters which enter the soil vertically to provide openings to allow greater air exchange. The vertical coulter alone provides very little weed control, but it increases the action of the rotary harrow that follows. The rotary harrow has numerous fingers to evenly distribute and maintain surface residue and potentially uproot small vegetation while operating at a shallow depth. A combination tool equipped with a vertical coulter and rotary harrow is currently being marketed by Great Plains[1] (e.g. Turbo-till). The high residue rotary hoe is a modified version of a standard rotary hoe designed to be

[1] Great Plains Mfg Inc., 1525 E. North Street, Salina, Kansas, 67401

compatible with high residue environments. The rotary hoe is a full-width blind cultivation tool that is used before or after crop emergence. The spoon like tip is designed to uproot weeds pre-emergence in the white thread stages (Bowman, 1997). The high residue rotary hoe has greater clearance for residue flow than a standard rotary hoe due to increased distance between the front and rear wheels. This design also allows the wheels to be self-cleaning with the wheel's movement removing residue from between the opposing parallel wheels. Although there are no results reported for high residue rotary hoe performance in no-till corn, Hooker et al. (1997) tested the implement in no-till soybean and reported that one pass of the rotary hoe did not control weeds. High residue inter-row cultivators are also commercially available, which are modified versions of a standard inter-row cultivator designed to handle high residue and no-till conditions. Most units consist of a residue cutting coulter followed by wide, flat sweeps operated 2 to 5 cm deep designed to undercut weeds and leave residue on the surface (Bowman, 1997). Eadie et al. (1992) reported that a high residue cultivator alone did not provide adequate weed control and needed to be supplemented with banded herbicide to provide in-row weed control. Additional research has also found banded herbicide followed by cultivation to provide acceptable weed control (Hanna et al., 2000; Paarlberg et al., 1998). In reduced tillage systems, adoption of banded herbicides can reduce weed control cost which in return can increase or maintain net returns (Cox et al., 1999; Mulder and Doll, 1993; Poston et al., 1992) and similar results could be found in conservation tillage systems.

The objective for this study was to develop integrated weed management strategies for conservation tillage corn that are less reliant on herbicides to reduce the potential for off-site movement and/or resistance development. Specifically, this study evaluated: 1) combinations of mechanical tools with and without herbicides for weed management in high residue corn 2) the impact of these management systems on surface residue cover, and 3) the production costs, breakeven price, and net returns for management in corn. Within these objectives we developed four hypotheses: 1) the combination of the vertical coulter/rotary harrow would provide weed control comparable to a burndown herbicide, while maintaining the surface residue level of a no-till system, 2) two to three passes of the rotary hoe would provide equivalent weed control to a soil-applied residual herbicide, while maintaining surface residue, 3) the inter-row cultivator would provide between row weed control comparable to soil-applied or post-emergence herbicides, while maintaining surface residue, and 4) banded soil-applied herbicides at planting would provide improved weed control over the cultivator alone by providing in-row weed control, while the cultivator provides only between-row weed control. In this integrated weed management approach, the benefits of conservation tillage in company with limited herbicide use are combined to achieve a more sustainable weed management system. This research is expected to help producers desiring to use less herbicide and tillage to better manage weeds on their farm.

Material and Methods

The research was conducted on The Pennsylvania State University Agronomy Farm at the Russell E. Larson Agricultural Research Center, located 16 kilometers southwest of State College, Pennsylvania (Latitude: 40° 43' N Longitude: 77° 56' W). The soils were predominately Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalf), with slopes varying from 0-3%. The Hagerstown series consists of deep, well-drained soils that formed in limestone residuum (Braker, 1981). Rainfall data was collected from local weather stations while temperature data was obtained from ZedX[2] using interpolated data from local weather stations. Cumulative growing degree days (GDD) were calculated using base 10 °C and max 30 °C from April 1 to harvest.

The study contained ten treatments and individual plots were 30 m long and 4.6 m wide consisting of six rows, spaced 76-cm apart. A description of experimental treatments is listed in Table 2.1 and timing of field operations is outlined in Table 2.2. The corn hybrid was Pioneer brand '36Y86', triple stack ('36Y86',NK603 ,TC1507 Cry1F + DAS-59122-7, Cry34/35Ab1), a 104-day relative maturity hybrid treated with 0.25 mg ai seed^{-1} clothianidin [C(*E*)]-*N*-[(2-chloro-5-thiazolyl)methyl]-*N′*-methyl-*N″*-nitroguanidine] (2008) or 0.25 mg ai seed^{-1} thiamethoxam [3-[(2-chloro-5-thiazolyl)methyl]tetrahydro-5-methyl-*N*-nitro-4*H*-1,3,5-oxadiazin-4-imine] (2009) planted at a seeding rate of 78,500 plants hectare^{-1} with a John Deere[3] 1780 no-till planter equipped with Dawn[4] row cleaners. The study was conducted in fields where corn for grain was produced in the previous year and the stalks were flail mowed in the fall. Prior to corn planting and to maximize yield, 206 kg ha^{-1} N as urea (46%) plus NBPT [N-(n-butyl) thiophosphoric triamide] urease inhibitor (Agrotain[5]) was broadcast applied. A starter fertilizer of 22 kg ha^{-1} N, 44 kg ha^{-1} P_2O_5, and 15 kg ha^{-1} K_20 was applied with an additional 34 kg ha^{-1} N side dressed as urea-ammonia nitrate (30%) at planting.

[2] ZedX Inc., 369 Rolling Ridge Drive, Bellefonte, PA 16823
[3] Deere & Company, One John Deere Place, Moline, IL 61265
[4] Dawn Equipment, P.O. Box 497, Sycamore, IL 60178
[5] AGROTAIN International LLC, 1 Angelica Street, St. Louis, MO 63147

Weed Populations

Weed population treatments consisted of a supplemental weed seed bank (here after referred to as the subplot) and the existing weed seed bank (resident). In the subplot, weed seeds were sown by hand in the late fall of each year in a 1.5 by 3 m band in the center of each plot. A mixture of 1500 seeds m^{-2} each giant foxtail (*Setaria faberi* Herrm., #[6] SETFA), common lambsquarters (*Chenopodium album* L., # CHEAL), redroot pigweed (*Amaranthus retroflexus* L., # AMARE), and horseweed (*Conyza Canadensis* L., # ERICA) and 750 seeds m^{-2} common ragweed (*Ambrosia artemisiifolia* L., # AMBEL) was broadcast in the subplot area to ensure an adequate weed population was present to effectively evaluate the different weed control treatments. These species are common in the region and the weed seeds were collected from local populations.

Weed Control

Burndown, broadcast soil-applied, and post-emergence herbicides were applied using a tractor mounted sprayer. The burndown application consisted of 0.84 kg ae ha^{-1} glyphosate [*N*-(phosphonomethyl)glycine] plus 0.28 kg ae ha^{-1} 2,4-D low volatile ester[(2,4-dichlorophenoxy)acetic acid]. The soil-applied broadcast and banded herbicides included 1.87 kg ai ha^{-1} s-metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-[(1*S*)-2-methoxy-1-methylethyl]acetamide], 0.19 kg ai ha^{-1} mesotrione [2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione], and 1.54 kg ai ha^{-1} atrazine [6-chloro-*N*-ethyl-*N′*-(1-methylethyl)-1,3,5-triazine-2,4-diamine]. The planter was equipped with small plot sprayer for application of

[6] Letters following this symbol are a Weed Science Society of America-approved computer code.

banded soil-applied herbicide. The herbicide was applied in a 30-cm band using a flat fan 4002E TeeJet®[7] tips positioned directly behind the planter units. Post-emergence herbicides included 0.027 kg ai ha^{-1} nicosulfuron [2-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]-*N,N*-dimethyl-3-pyridinecarboxamide], 0.0123 kg ai ha^{-1} rimsulfuron [*N*-[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]-3-(ethylsulfonyl)-2-pyridinesulfonamide], 0.84 kg ha^{-1} atrazine, and 0.28 kg ha^{-1} mesotrione applied at the V5 stage of corn growth. Corn growth stages were determined according to Ritchie et al. (1996). All herbicides were applied in water at 187 L ha^{-1} at 207 kPa.

The vertical coulter/rotary harrow, rotary hoe, and cultivator were substituted for a burndown, soil-applied residual, and post-emergence herbicides, respectively. The vertical coulter used in this study was constructed on a modified chisel plow frame using Yetter[8] vertical tillage attachments spaced 23 cm apart and was operated at 11.3 kilometers per hour (kph) (Figure 2.1). Water-filled barrels attached to the frame added about 500 kg of weight to increase penetration. The rotary harrow used in this study was a prototype tool developed by Phoenix Rotary Equipment[9] and was operated at 16.1 kph. The prototype had two sets of gangs (rather than a single set) designed to increase the activity of the implement in no-till systems in a single pass. In 2008, an early April operation (Table 2.2) of the vertical coulter/rotary harrow was performed in certain treatments. Prior to planting in May, a second rotary harrow operation was made to the same treatments. In contrast, a single vertical coulter/rotary harrow operation was performed prior to planting in May in 2009. The high residue rotary hoe used

[7] Spraying System Company, P.O. Box 7900, Wheaton, IL 60187
[8] Yetter Manufacturing, Inc, PO Box 358 109 S. McDonough, Colchester, IL 62326
[9] Phoenix Rotary Equipment, 33908 128th Street County Road 4, Waseca, MN 56093

was a 4.6 meter M & W[10] 1815MT operated at 16.1 kph with 272 kg of weight added to increase penetration. The high residue cultivator was a 6-row John Deere 886 equipped with 41-cm wide sweeps, disk hillers, and a Sukup Auto Guide®[11] guidance system operated at 11.3 kph. The guidance system allowed for a faster operating speed and reduces crop injury potential due to operator error. The cultivator's disk hillers were set at 5-10 degrees and 11-14 cm away from corn plants to pull soil and residue from the row. A second cultivation pass was conducted in 2009 and the disk hillers were removed. Rotary hoe and cultivator operations were based on soil moisture conditions and emerged weed size or potential for weed emergence and were performed when the implements would be most effective. In 2008, there were three rotary hoe operations compared to two rotary hoe operations in 2009. Wet weather in 2009 prevented a third rotary hoe operation. In addition, one cultivator operations was performed in 2008 compared to two in 2009. The second cultivator operation was added to further improve cultivator efficacy.

Date Collection

Timing of data collection is reported in Table 2.2. Corn population was determined in each plot after completing all weed control operations by counting corn plants in the center two rows for a length of 5.3 m. Percent corn surface residue from the previous crop and weed density were collected in each plot before any mechanical operation and following the first vertical coulter/rotary harrow (2008 only), planting, final rotary hoe, and final cultivator operation. Surface residue data was collected just prior to the next field operation and included

[10] M & W Gear Company, 10205 Sangamon Avenue, Gibson City, IL 60936
[11] Sukup Manufacturing Company, 1555 255th Street, Sheffield, IA 50475

only corn residue from the previous crop. Percent residue was measured using the line-transect method (Shelton et al., 1997). Weed density by species was collected using 0.25 m^2 quadrats with four 0.25 m^2 quadrats per plot within the subplot and from the resident weed population. In 2008, three 0.25 m^2 quadrats rather than four were sampled within the subplot for the initial weed count, but all following counts included four 0.25 m^2 quadrats. Weed dry matter was collected in late summer from each plot by removing total above-ground weed biomass from one 0.76 m by 3.0 m area within the subplot and from two within the resident population. The samples were separated by weed species, oven dried at 55 C for at least 72 hours and weighed. Crop grain yield was measured at harvest by hand harvesting two rows within the subplot for length of the subplot (3.0 m) and using a small plot combine to harvest the remaining corn from the center two rows of the resident population within each plot. The grain was weighted and corrected to 155 g kg^{-1} moisture content.

Statistical Analysis

Each of the ten treatments was replicated four times in a randomized complete block design. All data were analyzed with PROC MIXED in SAS (SAS, 2009). Means were separated using the Tukey-Kramer test at $P < 0.05$ to determine significant differences. A split-plot fixed effects model was used with treatment (main plot), subplot and resident weed area (split-plot), and the interaction between the two factors as fixed effect terms, with block and the treatment by block interaction as random effects. When the treatment by weed area interaction was significant the weed areas (subplot and resident) were analyzed separately. When treatments were not different at specific data collection periods, the treatment data was pooled to reflect only treatments present. Weed density data and individual weed species for weed biomass were log transformed ($\log_{10} x + 1$) as needed to reduce heterogeneity of variance and untransformed data is presented.

Economic Analysis

Enterprise budgets were computed to provide an economic comparision of treatments. Enterprise budgets provide an estimate of the potential revenue, expenses, and profit for a single enterprise and can be used to compare potential alternative enterprises (Kay et al., 2008). Enterprise budgets were calculated for each treatment using the Mississippi State Budget Generator v6.0 (Laughlin and Spurlock, 2008). Tractors and implements sizes are based on typical size for mixed crop and livestock farms of the Mid-Atlantic region. Production costs were based on 2009 data obtained as noted in Tables 2.3 and 2.4. A 7% interest rate for opportunity cost was charged from the date of operation or use of input until harvest. Land and management charges were not included in total production cost. Weed control costs were separated from total production cost and then further separated into herbicide, machinery, and labor cost for each treatment. Total production costs and the mean treatment yields were used to calculate breakeven prices. Breakeven price provides the minimum price needed to cover total production cost at a given yield and is calculated by dividing the total production cost by the treatment yield (Kay et al., 2008). In addition, net returns provide an estimate of returns above total cost and were calculated by multiplying treatment yields by an expected corn price and subtracting total production cost (Kay et al., 2008). Net returns assuming corn prices of

$0.138 kg^{-1}, $0.157 kg^{-1}, $0.177 kg^{-1}, and $0.197 kg^{-1} are presented. The range of prices was used to evaluate the sensitivity of changes in price on the profitability of the treatments.

Results

Climatic Conditions

Total rainfall from April 1 through November was 550 mm in 2008 (NRCS, 2008) and 575 mm in 2009 (EPA, 2009) (Table 2.5). The historical average total rainfall from April 1 through November is 713 mm (NCDC, 2009). Cumulative GDD from April 1 to harvest was 1531 in 2008 and 1521 in 2009 (Figure 2.2). The 30 year historical average cumulative GDD for the time period is 1539.

Corn Population

In comparing treatment effect on corn population, years were pooled because no interaction between year and treatment occurred. In 2008 corn populations averaged about 12,000 plants ha^{-1} less than 2009 (Figure 2.3). In general, none of the individual tillage tools consistently increased or decreased corn population, but the combination of the rotary hoe and cultivator reduced populations by an average of 8%.

Residue

Residue data were analyzed separately by year due to differences in the timing and number of mechanical operations within years (Table 2.2). In 2008, surface residue cover averaged 84% across the experimental site prior to any tillage or planting operations on April 8 (Table 2.6). After corn planting, residue cover in the vertical coulter/rotary harrow treatments were 15 percentage points lower (51 vs. 66%) than the no-till. After three rotary hoe operations, residue in the no-till averaged 58%, whereas the rotary hoe treatment was reduced to 48% and was similar to the vertical coulter/rotary harrow with and without the rotary hoe (41% mean residue cover) on June 16. Following cultivator operations, the no-till and vertical coulter/rotary harrow only treatments averaged 56 and 40% residue cover, compared to an average of only 26% in treatments receiving one pass with the cultivator on July 16. In 2009, the previous corn crop surface residue averaged 85% across the experimental site prior to any tillage or planting operations. After corn planting, the vertical coulter/rotary harrow treatments were 14 percentage points lower (48 vs. 62%) than the no-till treatments. Three rotary hoe operations did not impact residue cover in 2009. The no-till and rotary hoe operation alone averaged 47%, whereas the vertical coulter/rotary harrow with and without the rotary hoe averaged 33% residue cover on June 16. Residue cover across treatments with two cultivator passes averaged only 21%, compared to 43% in the no-till and 34% in the vertical coulter/rotary harrow with and without the rotary hoe.

Weed Density

Weed data was separated by years due to differences in the number of mechanical weed control operations within years and timing of data collection. In the 2008 weed subplot, prior to the initial vertical coulter/rotary harrow operations, no weeds had emerged (April 8; Table 2.7). On April 30, average weed densities ranged from 73 to 90 plants m^{-2} with giant foxtail being the most common species observed, representing 61% of the total weed density. The vertical coulter and rotary harrow operation did not influence weed density at this early date. Following planting and some of the management treatments (vertical coulter/rotary harrow, burndown and soil-applied herbicides), average weed density ranged from 5 to 65 plants m^{-2} and common ragweed and giant foxtail comprised 37 and 47%, of the weeds present on May 13. Treatments with broadcast soil-applied herbicides averaged less than 10 plants m^{-2}, compared to the weedy check with 65 plants m^{-2} and the remaining treatments weed densities ranged from 17 to 32 plants m^{-2}. Average weed densities on June 17 ranged from 6 to 156 plants m^{-2} and common ragweed, giant foxtail, and common lambsquarters comprised 26, 28, and 30%, respectively, of the total weed density. Treatments with broadcast soil-applied herbicide had the lowest weed density with less than 10 plants m^{-2}. In contrast, average weed density in treatments including the rotary hoe or banded herbicides ranged from 47 to 79 plants m^{-2} and treatments without the rotary hoe or soil-applied herbicides ranging from 127 to 156 plants m^{-2}. Compared to the vertical coulter/rotary harrow treatment, the vertical coulter/rotary harrow + rotary hoe reduced weeds by 38%. Conversely, the rotary hoe did not reduce weed density when a banded soil-applied herbicide was included. By July 16, average weed densities ranged from 12 to 102 plants m^{-2} and the composition of the weed community was diverse with no weed species representing more than 25% of the total emerged weeds. Average weed densities in treatments including broadcast soil-applied or post-emergence herbicides averaged less than 34 plants m^{-2} whereas treatments without broadcast soil-applied or post-emergence herbicides ranged from 75 to 102 plants m^{-2}. Weed emergence in treatments within the resident weed areas were generally similar to those in the subplots, although weed densities were lower in the resident plots compared to the subplots, depending on the sampling dates and treatment. In addition, there were no treatment differences in the resident populations on April 30 and May 13 and the density in the resident population increased from 15% of the subplot on April 30 to 49% on July 16.

In 2009, prior to vertical coulter/rotary harrow operations the average density was 7 plants m^{-2} with giant foxtail representing 87% of the total weed density (Table 2.8). Following planting and some of the management treatments (vertical coulter/rotary harrow, burndown and soil-applied herbicides), weed densities ranged from 0 to 2 plants m^{-2} with giant foxtail and others representing 21 and 79% of the emerged weeds. On June 12 average weed densities ranged from 4 to 293 plants m^{-2} with common lambsquarters and redroot pigweed comprising 26 and 51% of the emerged weeds. Treatments with broadcast soil-applied herbicides averaged less than 4 plants m^{-2}. In contrast, average weed densities in banded herbicide treatments ranged from 97 to 149 plants m^{-2} and treatments without soil-applied residual ranged from 218 to 293 plants m^{-2}. The rotary hoe did not reduce weed density compared to the weedy check and the vertical coulter/rotary harrow alone. By July 2, average weed densities ranged from 9 to 212 plants m^{-2} and the emerged weed composition was diverse, but giant foxtail and redroot pigweed comprised 31 and 39% of the total weed density. Weed densities in treatments including broadcast soil-applied or post-emergence herbicides averaged less than 25 plants m^{-2}, whereas banded treatments ranged from 42 to 44 plants m^{-2} and treatments without soil-applied or post-emergence herbicides ranged from 89 to 212 plants m^{-2}. Weed emergence in the resident weed areas was generally similar to those in the subplots, although densities in the resident plots averaged 39% of the subplots, depending on the sampling dates and treatment.

Weed Biomass

Weed biomass was affected by the weed management treatments, but the nature of these effects depended on the study year (Table 2.9). In the 2008 weed subplots, average weed biomass ranged from 11 to 9531 kg ha^{-1} and from 1 to 3931 kg ha^{-1} in the resident weed areas (Table 2.10). In the subplot, common ragweed comprised the majority of the weed biomass with 61% of the total. Weed biomass in treatments including broadcast soil-applied or post-emergence herbicides averaged less than 343 kg ha^{-1}, whereas banded treatments ranged from 1306 to 1910 kg ha^{-1} and treatments without soil-applied or post-emergence herbicides ranged from 3799 to 9531 kg ha^{-1}. Although still producing on average 1265 kg ha^{-1} more dry matter, weed control results with banded herbicide were similar to broadcast soil-applied herbicides. Compared to the weedy check, the vertical coulter/rotary harrow + cultivator and the vertical coulter/rotary harrow + rotary hoe + cultivator reduced weed biomass 44 and 60%. Weed biomass trends among the treatments in the resident weed areas were generally similar to those in the subplots, although when averaged across treatments, the resident weed biomass was 65% lower than the subplot weed biomass.

In the 2009 weed subplots, weed biomass ranged from 13 to 4481 kg ha^{-1} and from 5 to 3507 kg ha^{-1} in the resident weed areas (Table 2.11). In the subplot, giant foxtail and redroot pigweed comprised 24 and 50% of the total biomass. Weed biomass in treatments including broadcast soil-applied or post-emergence herbicides averaged less than 63 kg ha^{-1}, whereas banded treatments ranged from 376 to 384 kg ha^{-1} and treatments without soil-applied or post-emergence herbicides ranged from 2369 to 4481 kg ha^{-1}. Weed control with banded herbicide was similar to broadcast soil-applied herbicides. Compared to the weedy check, the vertical coulter/rotary harrow + rotary hoe + cultivator reduced weed biomass 47%. Differences in weed biomass between treatments in the resident weed areas were generally similar to those in the subplots, although when averaged across treatments, resident biomass was 44% lower than the subplot weed biomass.

Corn Grain Yield

Corn grain yield was affected by the weed management treatments, but the nature of these effects depended on the study year (Table 2.12). In 2008, average corn yields ranged from 1494 to 10017 kg ha^{-1} in the subplot and from 5336 to 9882 kg ha^{-1} in the resident weed population (Table 2.13). Average corn yield in treatments including broadcast soil-applied or post-emergence herbicides averaged greater than 9384 kg ha^{-1}. In contrast, banded treatments ranged from 7736 to 7847 kg ha^{-1}, and treatments without soil-applied or post-emergence herbicides ranged from 1494 to 5249 kg ha^{-1}. Although averaging only 7792 kg ha^{-1} across banded herbicide treatments, yield was not significantly different than that for broadcast soil-applied herbicides. Compared to the weedy check, the vertical coulter/rotary harrow + cultivator and the vertical coulter/rotary harrow + rotary hoe + cultivator yielded 65 and 72% higher. Conversely, the vertical coulter/rotary harrow + cultivator and the vertical coulter/rotary harrow + rotary hoe + cultivator yielded 57 and 48% less than the conventional no-till. Corn yield trends among the treatments in the resident weed areas were generally similar to those in the subplots. Corn yield in treatments including broadcast soil-applied or post-emergence herbicides were similar between the subplot and resident areas. In contrast, treatments without broadcast soil-applied or post-emergence herbicides yielded 2060 to 3848 kg ha^{-1} more in the resident weed population than in the subplot as a result of differences in weed severity. The weedy check and the treatments without herbicides did not achieve the yield of the highest yielding treatments.

In 2009, because there was no significant area or treatment by area interaction the subplot and resident areas were pooled, and average corn yields ranged from 10,507 to 13,266 kg ha^{-1} (Table 2.13). Average corn yield in treatments including herbicides averaged greater than 12,197 kg ha^{-1} compared to treatments without herbicides which ranged from 10,507 to 12,005 kg ha^{-1}. Compared to the weedy check, the vertical coulter/rotary harrow + cultivator and the vertical coulter/rotary harrow + rotary hoe + cultivator yielded 12% higher. Conversely, the vertical coulter/rotary harrow + cultivator and the vertical coulter/rotary harrow + rotary hoe + cultivator yielded only 10% lower than the vertical coulter/rotary harrow + herbicides treatment.

Production Costs

Differences in total production cost between years were a result of differences in weed control costs (Tables 2.14 and 2.15). All other costs (except drying costs) were held constant at \$876.24 ha^{-1} for fertilizer, seed, planting, and harvesting. Due to differences in yield, corn drying costs were different between subplot and resident areas. Differences in the cost of weed control between years were due to differences in the number of machinery operations (Table 2.2). In 2008, treatments total weed control cost ranged from \$0 to \$170 ha^{-1}. With less reliance on herbicides, herbicide cost decreased from \$139 ha^{-1}, while machinery and labor costs increased up to \$74 ha^{-1} and \$19 ha^{-1}, respectively (Table 2.14). In 2009, total weed control cost ranged from \$0 to \$194 ha^{-1}. Herbicide cost decreased from \$139 ha^{-1} and machinery and labor costs increased up to \$80 ha^{-1} and \$18 ha^{-1}, respectively with less reliance on herbicides (Table 2.15). The herbicides + cultivator treatment was the most expensive weed control program in both 2008 and 2009. Of the mechanical treatments, the vertical coulter/rotary harrow + cultivator treatment was the least expensive. One pass of the vertical coulter/rotary harrow cost \$13.76 ha^{-1} less than a glyphosate + 2, 4-D burndown application. Three passes with the rotary hoe and two passes with the cultivator cost less than either a soil-applied broadcast or post-emergence herbicide application. Banded herbicide plus two passes with the cultivator was similar in cost to a post-emergence herbicide application and the banded herbicide plus two passes with the cultivator was \$15.57 ha^{-1} less than the soil-applied broadcast. The use of the auto guide system on the cultivator increased the initial cost of the cultivator by \$6,000, but the increase in operating speed reduced labor cost by \$14.93 ha^{-1} (Table 2.3). The sprayer system for banding herbicide on the planter increased the cost of the planter \$3.33 ha^{-1}. The rotary hoe was the least expensive weed control tool at \$7.14 ha^{-1} per pass, but two to three passes were utilized in this experiment. By reducing the amount of herbicide applied by 60% through banding, the cost of the soil residual herbicide was reduced proportionately by 60%.

While total production costs were similar between years, the higher yields in 2009 resulted in lower breakeven prices than in 2008. Total production cost ranged from \$882 to \$1111 ha^{-1} in 2008 (Table 2.14) and from \$918 to \$1126 ha^{-1} in 2009 (Table 2.15). In 2008 breakeven prices ranged from \$0.107 to \$0.590 kg^{-1}, but only ranged from \$0.081 to \$0.091 kg^{-1}

in 2009. In 2008, the conventional no-till had the lowest breakeven corn price at \$0.107 kg^{-1} and the weedy check the highest at \$0.590 kg^{-1}. The greater reliance on mechanical weed control resulted in a lower yield which increased the breakeven price. In 2009, the conventional no-till treatment had the lowest breakeven corn price at \$0.082 kg^{-1} and the herbicide + cultivator treatment had the highest breakeven corn price at \$0.091 kg^{-1}.

Higher yields resulted in higher net returns in 2009 compared to 2008 (Tables 2.16 and 2.17). At the low corn price scenario of 0.138 kg^{-1}, the net returns ranged from -\$676 to \$312 ha^{-1} in 2008 (Table 2.16) whereas in 2009 net returns ranged from \$530 to \$739 ha^{-1}(Table 2.17). In the 2008 resident area, treatments with more reliance on mechanical implements had lower breakeven prices than in the subplot whereas the breakeven price of treatments relying on broadcast herbicides was more consistent between subplot and resident. In 2008, treatments including broadcast soil-applied residual or post-emergence herbicide had the highest net returns and treatments without broadcast soil-applied residual or post-emergence herbicides had the lowest, with the banded herbicides treatments in between. Conversely, 2009 net returns were similar across treatments because yields were less variable. Treatments including soil-applied or post-emergence herbicides provided positive net returns across years for a range of corn prices.

Discussion

Corn populations were slightly impacted by the mechanical implements. The lower population in 2008 was likely a result of cool, wet conditions, followed by a prolonged dry period following planting, leading to surface crusting and reduced emergence. The first rotary hoe operation was performed as the crop was emerging under crusted conditions, but did not increase corn populations. On farms relying on tillage, one of the main purposes of the rotary hoe is to increase crop population by breaking the soil crust. In no-till, the rotary hoe's ability to reduce the impact of soil crusting may be less effective than in tilled systems. Corn population was reduced (8%) from the combination of the rotary hoe plus cultivator with both contributing to the reduction. Previous research found reductions in corn population from the rotary hoe ranged from 0 to 14% (Cox et al., 1999; Mohler et al., 1997; Vangessel et al., 1995) while, inter-row cultivation did not reduce corn populations in conventional and reduced-till systems (Cox et al., 1999; Mulder and Doll, 1993). However, these studies were not conducted in no-till and used a different type of cultivator (Danish S-tine style). The high residue cultivator used in this study can create clods, which can be thrown onto the crop potentially causing injury. Paarlberg et al. (1998) reported high residue cultivation in no-till had no effect on corn population, but unlike this study, shields were used to protect the crop.

The vertical coulter/rotary harrow and the cultivator's impact on surface residue raises concerns for soil erosion. Our hypothesis that the combination of the vertical coulter/rotary harrow would provide weed control compared to a burndown herbicide, while maintaining residue levels of a no-till system is partially rejected. While the vertical coulter/rotary harrow provided the weed control of a burndown herbicide, this combination reduced residue levels by about 15% compared to no-till. However, the vertical coulter/rotary harrow treatments remained above the 30% conservation level as defined by the Conservation Technology Information Center (CTIC, 2009) and the combination could be a suitable shallow tillage option for pre-plant weed control in conservation tillage systems. Also, our hypothesis that two to three passes of the rotary hoe would provide equivalent weed control to a soil-applied residual herbicide, while maintaining surface residue is partially rejected. In this study, the rotary hoe did not have a substantial impact on surface residue nor did it effectively control weeds. Although the rotary hoe reduced weed density in 2008, it did not reduce weed biomass. Previous research suggests that the rotary hoe is less effective under conditions with greater than 30% residue cover (Cox et al., 1999; Springman, 1989). In this study, the rotary hoe was operated in about 50% surface residue, so if the residue amounts were less than 30% or perhaps differed in quality, the rotary hoe may have been a more effective weed control tool. The cultivator had the single greatest impact on residue cover and this finding partially rejects our hypothesis that the inter-row cultivator would provide the between row weed control comparable to soil-applied or post-emergence herbicides, while maintaining surface residue. However, the timing of cultivator operations relative to crop growth and soil conditions must be considered when evaluating soil erosion potential. Following cultivation in this study, corn was in the V5 to V6 growth stage and entering a period of rapid growth (Hoeft et al., 2000) which should help provide canopy cover and potentially reduce erosion. Also, cultivation increases the surface roughness and helps break up crusted soils potentially increasing water infiltration and reducing runoff (Alberts and Neibling, 1994). Because soil inversion is nominal with the rotary hoe and cultivator, the lower levels of residue observed with these mechanical tools could be the result of reducing the residue size to smaller than the 2.4 mm diameter minimum required under the line transect method (Shelton et al., 1997) and/or redistribution of the residue on the surface from the inter-row into the crop row with the cultivator. Finally, corn stalks were shredded in the fall prior to spring management in this study and Shelton et al.

(1995) reported that shredded stalks are more susceptible to losses caused by the mechanical implements used in this study. In order to maintain residue cover in combination with the mechanical weed control tools used in this study, spring stalk shredding or no stalk shredding could help maintain higher residue levels.

The results from this study demonstrate the ability to maintain weed control and yield, while incorporating certain mechanical tools and herbicide combinations under high residue conditions. In contrast, the mechanical only treatment results in this study disagree with previous research in conservation tillage systems that reported three rotary hoe and two cultivation passes produced yields equal to soil-applied herbicides (Mulder and Doll, 1993). The high surface residue reducing the effectiveness of the rotary hoe could be partially responsible for this difference. It was anticipated that the early season vertical coulter/rotary harrow would create a flush of weeds through warmer temperatures and soil disturbance and the rotary harrow prior to planting was projected to control the weeds prior to planting. However, following planting there was no difference in weed density between this treatment and the conventional no-till. This result, along with concerns over increased soil erosion potential from the early spring tillage, was the basis for removing the early April vertical coulter/rotary harrow timing in 2009. Although weed control was generally better with the combination of banded herbicide plus cultivation than with cultivation alone, our results agree with Eadie et al. (1992) who reported that depending on the year, the cultivator alone can produce corn yields similar to the combination treatment in no-till. However, other research reported that banded herbicide plus cultivation achieved higher yields than cultivation alone when weed severity was high (Krausz et al., 1995). We observed similar results in the 2008 subplots where weed biomass was greater than 9500 kg ha^{-1} in the weedy check treatment (Table 2.10). Also in agreement with Eadie et al. (1992), our results showed that banded herbicides combined with cultivation can equal broadcast herbicides in both weed control efficacy and corn yield. The findings of our research support our hypothesis that banded soil-applied herbicides at planting would provide improved weed control over the cultivator alone by providing in-row weed control, while the cultivator provided between-row weed control. While the frequency of cultivation was not tested in this study and varied between years (one in 2008 and two in 2009), the number of passes could influence performance. Buhler et al. (1995) reported that a second inter-row cultivation increased weed control from 45 to 64% in a no-till system. However, 64% control is less than ideal and our results found cultivation alone was not as effective as a post-emergence herbicide. Weather and soil conditions along with the size and composition of the weed seed bank may play an important role in the effectiveness of cultivation. Dry soil conditions created challenges in maintaining proper operating depth and wet soil conditions created soil masses that did not separate the soil from the root system of weeds. In wet soil, small weed seedling roots are left undisturbed and continued to grow. In systems relying on cultivation, scouting may be necessary following the first cultivation to determine if a second operation is warranted.

The incorporation of the mechanical implements in this study helped decrease herbicide use potentially reducing the potential for herbicide pollution. However, in this study mechanical implements alone did not effectively manage the weeds and some herbicide was necessary to help maintain corn grain yield. In particular, the rotary hoe did not adequately substitute for soil-applied residual herbicides, so early season weed competition was likely a factor in these treatments. In contrast, banded soil-applied residual herbicides with cultivation provided effective weed control and maintained corn yield, while at the same time reducing herbicide use by 60%. Guillard et al. (1999) reported that atrazine applied in a 25-cm band followed by cultivation maintained corn yields and reduced leaching losses to groundwater by about 75% compared to broadcast applications. The reduction in herbicide leaching with banded applications may be attributed to the non-treated area acting as a natural filter helping to reduce herbicide losses (Gaynor and Wesenbeeck, 1995).

Herbicide-resistant weeds evolve with frequent herbicide use (Heap, 1997). Replacing vulnerable herbicides with effective mechanical weed control could slow the development of herbicide-resistant weeds. In addition, post-emergence cultivation could be used as an alternative and potentially lower cost alternative to an additional herbicide application for rescue control of resistant weed escapes. In this study, common ragweed, common lambsquarters, and horseweed, three weeds previously identified as herbicide-resistant in the region (Heap, 2010), were controlled with cultivation provided they were not directly in the corn rows. In this study, cultivation following a broad spectrum soil-applied broadcast herbicide produced results similar to the broad spectrum broadcast herbicide alone; however unlike herbicides, cultivation is equally effective on both herbicide-resistant and susceptible weed biotypes. Conversely, cultivation can also result in the emergence of additional weeds and although the late emerging weeds are less likely to compete with the crop, they can produce seeds, and reduce crop quality and impact the harvest of some crops. Krausz et al. (1995) reported that cultivation created favorable conditions for late emerging ivyleaf morningglory (*Ipomea hederacea* L.), but the competitive corn canopy prevented the plants from maturing and producing seeds. Although not quantified in this study, late emerging weeds following cultivation appeared to produce some seeds which could be a concern in future years. Scouting the field following the first cultivation to determine if a second operation is warranted would help prevent successful late emerging weeds from going to seed.

Weed severity and management along with growing conditions (temperature and rainfall) helped determine grain yield which in turn influences the net returns. Reducing herbicide inputs decreases the cost of weed control, but yield must be maintained or net return is reduced. In addition, the herbicide program as well as equipment cost, size, and operating speeds will strongly influence cost comparisons between mechanical and chemical weed control. Cox et al. (1999) reported that weed management costs were higher with chemical weed control, but the higher yields increased net returns compared to alternative management programs. Mohler et al. (1997) reported that weed management costs were similar between mechanical and chemical treatments, but net returns tended to be lower with mechanical treatments. The herbicide programs used in our study are broader spectrum and higher cost than the herbicides used in their study, which might further impact net return. In addition, operation speed will impact the cost with slower operating speeds decreasing the area covered per hour and increasing the cost per hectare. A benefit of the mechanical tools investigated in this study is the relatively fast operating speeds allowed reducing their potential cost. The cultivator with the guidance system allowed for an increase in the operating speed by 4.9 kph. Paarlberg (1998) reported that increasing cultivator operating speed in no-till from 6.4 to 11.2 kph reduced costs and had a positive or neutral effect on weed control. Operator experience, field size, and field conditions would alter the speed of operation and the cost of the mechanical implements. The economic analysis in this project was conducted with implements that are typical in the Mid-Atlantic region due to farm and field size. In the Midwest or regions where farm and field size are larger, the implements could be wider. This would increase the hectares that could be covered in an hour and decrease the cost per hectare of the implements. In addition, small field size reduces the efficiency operations due to constantly turning around and in larger fields with less turning around would allow for an increased efficiency of the operations which could also reduce the cost per hectare.

The treatments relying solely on mechanical weed tools may have the potential to be adopted by organic farmers. Although both weed control and yield were reduced, the organic price premium for corn could provide higher net returns than conventional production even if yields were slightly lower. Net returns using an organic premium were not calculated in this study, since inputs other than some weed control were conventional. Nutrient sources for organic systems include legumes, manures, compost and other natural fertilizer products and performance of the mechanical weed tools were not evaluated in these systems. Previous research has had some success with cultivation in no-till corn following alfalfa, but herbicides were used to kill the alfalfa prior to planting corn (Buhler et al., 1994). Teasdale and Rosecrance (2003) reported the cultivator was less effective in cover crop residue when the cover crop was mowed versus disked. Current research is examining the potential for high residue cultivation in organic systems relying on rolled cover crop mulches (Curran et al., 2009a; Curran et al., 2009b; Mirsky et al., 2009). Further research on the effectiveness of this tool in cover crops and organic systems is needed.

Conclusions

Overall, mechanical tillage implements alone did not provide adequate weed control, whereas integration with reduced herbicide inputs maintained acceptable weed control, yields, and production cost. The vertical coulter/rotary harrow combination reduced residue cover, but maintained weed control and yields, while reducing production costs compared to a burndown herbicide. The high residue rotary hoe, while having minimum effect on residue, was not an effective weed control tool. Although the high residue cultivator reduced production costs relative to herbicide-based programs, it also reduced surface residue and when used alone did not provide weed control or corn yields comparable to a program relying on post-emergence herbicides. Banded herbicides followed by the cultivator provided weed control, yields, and net returns similar to a soil-applied broadcast treatment. Combinations of herbicides and mechanical tools used under the proper weather and soil conditions have the potential to reduce herbicide use, while providing adequate weeds control, acceptable yield, and net returns.

Table 2.1. Description of experimental treatments investigated in corn at Rock Springs in 2008 and 2009.

		Supplemental Herbicide†			
			Soil-Applied Residual		
Trt. No.	Treatment	Pre-Plant Burndown	Broadcast	Banded	Post-Emergence
1	Conventional No-Till	X	X		
2	Herbicides + Cultivator	X	X		
3	VC/RH + Herbicides		X		
4	VC/RH + Hoe + Post				X
5	Burndown + Hoe + Cultivator	X			
6	VC/RH + Hoe + Cultivator (Banded)			X	
7	VC/RH + Cultivator (Banded)			X	
8	VC/RH + Hoe + Cultivator				
9	VC/RH + Cultivator				
10	Weedy Check				

† Herbicide applications were made to treatments indicated by an “X”.

Trt.No. = treatment number, VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe.

Figure 2.1. Mechanical weed control implements. From clockwise (A) vertical coulter, (B) rotary harrow, (C) rotary hoe, and (D) cultivator.

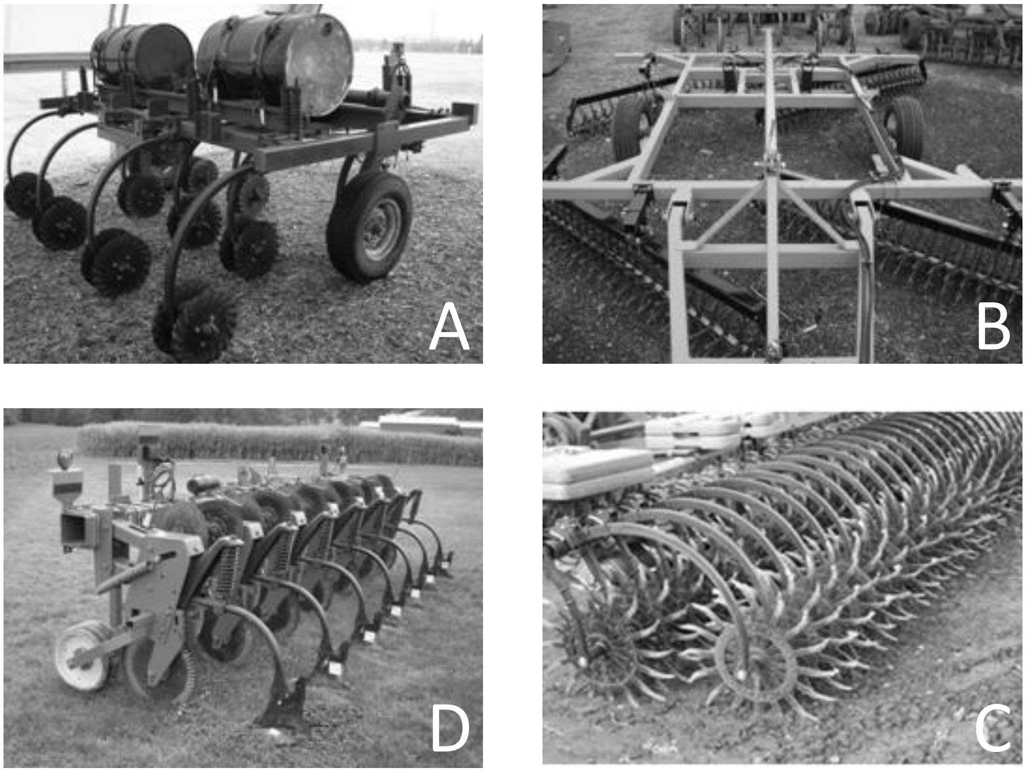


Table 2.2. Timing of field operations and measurements for corn in 2008 and 2009.

Operation	2008		2009	
	Date	DAP†	Date	DAP
Baseline Residue Count	8-Apr	-29	28-Apr	-15
Baseline Weed Count	8-Apr	-29	11-May	-2
1st VC/RH	9-Apr	-28	12-May	-1
Post VC/RH Residue Count	11-Apr	-26	—	—
Post VC/RH Weed Count	30-Apr	-7	—	—
2nd RH	6-May	-1	—	—
Plant Corn (& Band Treatments)	7-May	0	13-May	0
Burndown and Soil-Applied Herbicides	7-May	0	15-May	2
Post Planting Weed Count	13-May	6	19-May	6
Post Planting Residue Count	23-May	16	20-May	7
1st Rotary Hoe	26-May	19	22-May	9
2nd Rotary Hoe	2-Jun	26	31-May	18
3rd Rotary Hoe	9-Jun	33	—	—
Post Rotary Hoe Residue Count	16-Jun	40	12-Jun	30
Post Rotary Hoe Weed Count	17-Jun	41	12-Jun	30
Post Herbicide Treatment	18-Jun	42	14-Jun	32
1st Cultivation	18-Jun	42	16-Jun	34
2nd Cultivation	—	—	24-Jun	42
Post Cultivation Residue Count	16-Jul	70	25-Jun	44
Post Cultivation Weed Count	19-Jul	73	2-Jul	50
Corn Population Count	19-Jul	73	25-Jun	43
Weed Biomass Collection	27-Aug	112	25-Aug	104
Corn Harvest	4-Nov	181	14-Nov	185

† DAP = Days after planting. Negative value indicates operation occurred prior to planting.

VC/RH = vertical coulter/rotary harrow.

Table 2.3. Description and price of tractors and implements investigated in corn (2009 costs).

		Tractor Size (Kw)	Width / Capacity	Purchase Price ($)	Cost ha^{-1} ($ ha^{-1})	Operating Speed (kph)	Efficiency (%)
Tractor	Tractor 1	56	—	29,000†	—	—	—
	Tractor 2	78	—	71,000†	—	—	—
	Tractor 3	97	—	91,000†	—	—	—
Implement	Boom Sprayer	56	15.2 m	21,000†	7.22	8.1	65
	Vertical Coulter	78	4.3 m	22,582‡	20.66	11.3	70
	Rotary Harrow	78	4.6 m	15,000§	11.74	16.1	70
	Spinner Spreader	56	10.6 m^3	8,000¶	13.49	—	—
	No-till Planter	78	6 Rows / 4.6 m	25,000†	55.38	6.4	50
	No-till Planter w/Banding	78	6 Rows / 4.6 m	28,145#	58.71	6.4	50
	Rotary Hoe	56	4.6 m	7,140†	7.14	16.1	70
	Hi-Res Cultivator	97	6 Rows / 4.6 m	23,000†	39.02	6.4	70
	Hi-Res Cultivator w/Guide	97	6 Rows / 4.6 m	28,000†	24.09	11.3	70
	Grain Cart	56	12.3 m^3	5,714¶	—	—	—
	Stalk Shredder	97	4.6 m	17,250†	36.42	8.1	70

† Price obtained from Lazarus (2009).

‡ Price obtained from Wil-Rich[12] for similar implement (personal communication, 2009).

§Price obtained from Phoenix Rotary Equipment for prototype implement (personal communication, 2009).

¶ Price obtained from Jayson Harper (personal communication, 2009).

Price of no-till planter plus cost of 757 liter sprayer and banding system.

Kw = Kilowatt, KPH = Kilometers per hour.

[12] Wil-Rich LLC, 17885 Highway 13, PO Box 1030, Wahpeton, ND 58075

Table 2.4. Cost of custom operations and inputs for corn production (2009 input costs).

		Price ($)	Units
Custom Operations	Apply Lime	29.65†	hectare
	Combine Corn	75.86†	hectare
	Soil Test	4.94‡	hectare
Inputs	Corn Seed	247.50§	hectare
	Urea w/Agrotain®	277.37§	hectare
	13-26-9 Starter	85.25§	hectare
	30% UAN	39.56§	hectare
	Burndown herbicide	38.94¶	hectare
	Soil-applied broadcast herbicide	99.83¶	hectare
	Soil-applied banded herbicide	39.96¶	hectare
	Post-emergence herbicide	85.50¶	hectare
	Labor	12.50‡	hour
	Diesel	0.55§	liter

† Price obtained from Pike (2009).

‡ Price obtained from Jayson Harper (personal communication, 2009).

§ Price obtained from Penn State Agronomy Farm 2009 input prices (personal communication, 2009).

¶ Price obtained from William Curran (personal communication, 2009).

Table 2.5. Rainfall from April 1 through November at Rock Springs in 2008 and 2009 season.

Year	Precipitation								
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Total
	mm								
2008	94	92	74	92	41	110	47	38	588
2009	53	95	107	109	46	74	91	22	597
Historic Ave	80	94	109	91	86	93	74	86	713

Figure 2.2. Cumulative Growing Degree Days from April 1 to harvest at Rock Springs in 2008 and 2009.

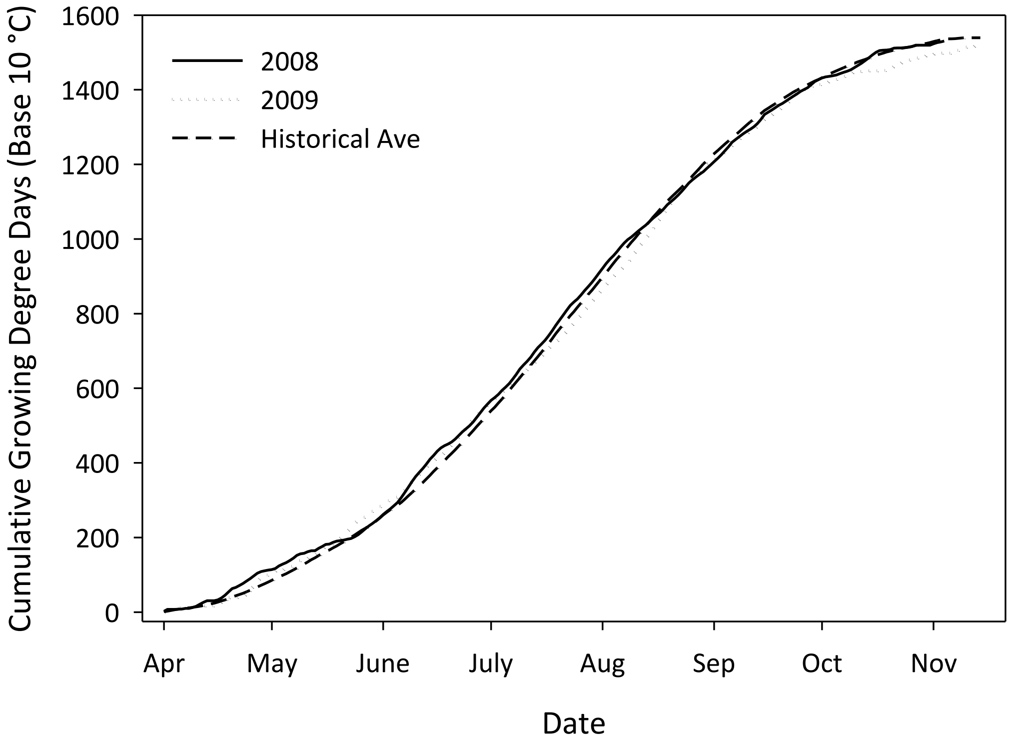
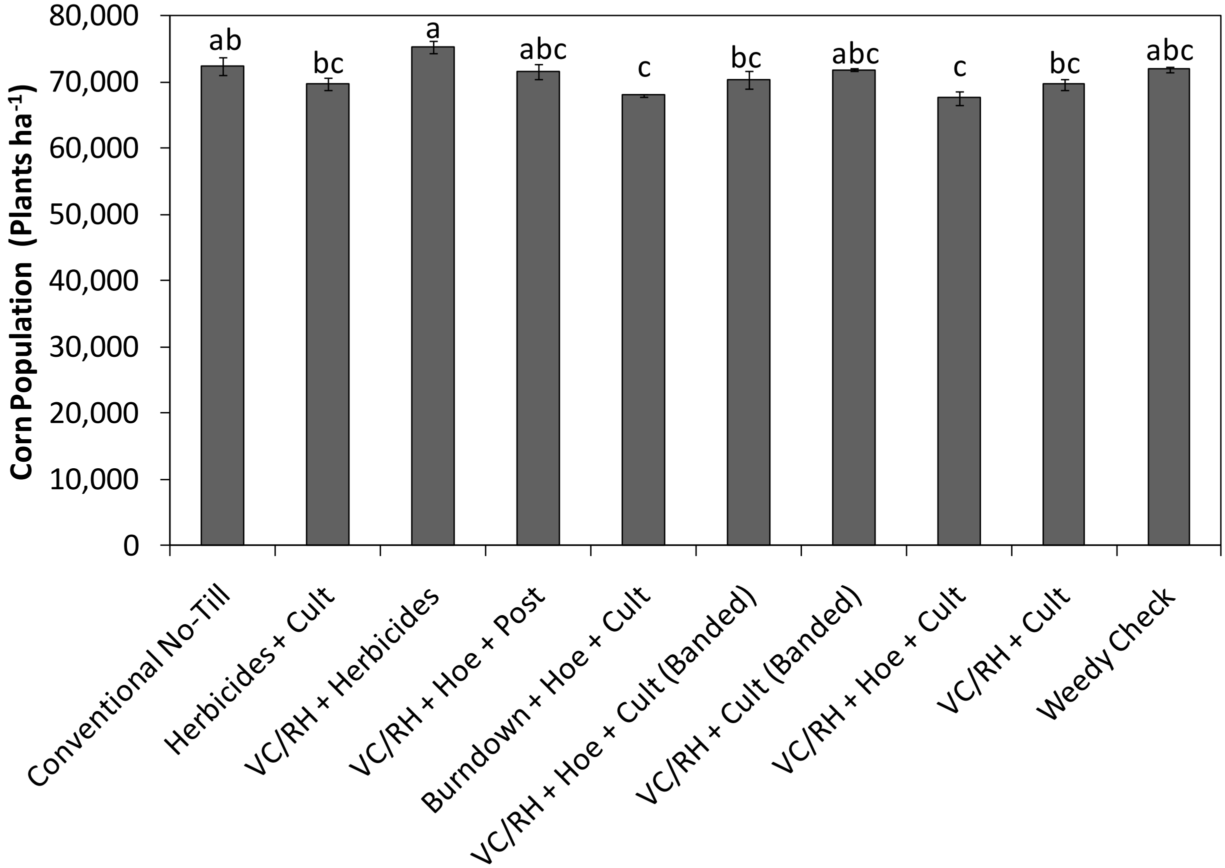


Figure 2.3. Mean† corn population following weed control operations in 2008 and 2009. Years were pooled.



† Similar letters indicate no significant difference between treatments at $p<0.05$ (Tukey-Kramer mean separation test). Standard Error bars provided for each treatment mean.

VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Table 2.6. Mean† surface residue levels following weed control operations in corn in 2008 and 2009.

Treatment‡	2008							2009						
	8-Apr	23-May		16-Jun		16-Jul		28-Apr	20-May		12-Jun		26-Jun	
	Residue (%)													
No-Till	84	66	a	58	a	56	a	85	62	a	47	a	43	a
VC/RH	—	51	b	42	b	40	b	—	48	b	33	b	34	b
Hoe	—	—		48	b	—		—	—		46	a	—	
VC/RH + Hoe	—	—		39	b	31	bc	—	—		33	b	34	b
Cult	—	—		—		29	bc	—	—		—		21	c
Hoe + Cult	—	—		—		33	bc	—	—		—		23	c
VC/RH + Cult	—	—		—		22	c	—	—		—		20	c
VC/RH + Hoe + Cult	—	—		—		21	c	—	—		—		18	c

† Similar letters in a column indicate no significant difference between treatments at $p<0.05$ (Tukey-Kramer mean separation test).

‡ Residue measurements from treatments that did not differ in at collection date were combined.

VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Table 2.7. Mean† weed density by corn treatment in 2008. Analyzed separately by dates, weed species, and subplot and resident areas.

Date	Treatment‡	Trt. No.	Subplot: AMARE		AMBEL		CHEAL		SETFA		Other§		Total¶		Resident: Total		Percent of Subplot
			Weed Density (Plants m^{-2})														
8-Apr	Baseline	1-10	0.0		0.0		0.0		0.0		0.0		0.0		0.0		—
30-Apr	Weedy Check	1,2,5,10	2.3	n.s.	23.2	n.s.	13.3	n.s.	51.2	n.s.	0.0		90.2	n.s.	9.0	n.s.	10
	VC/RH	3,4,6-9	2.3	n.s.	14.2	n.s.	8.3	n.s.	48.1	n.s.	0.0		72.9	n.s.	14.1	n.s.	19
13-May	Conventional No-Till	1,2	0.0	n.s.	3.8	b	1.3	n.s.	4.1	cd	0.3	b	9.7	cd	1.1	n.s.	12
Post	VC/RH + Herbicides	3	0.0	n.s.	2.3	ab	1.3	n.s.	1.3	d	0.3	ab	5.3	d	1.3	n.s.	23
planting	Burndown	5	0.0	n.s.	13.7	ab	4.3	n.s.	13.3	ab	0.3	ab	31.7	ab	1.0	n.s.	3
	VC/RH (Banded)	6,7	0.0	n.s.	7.0	ab	1.0	n.s.	8.5	bc	0.3	b	16.9	bc	2.5	n.s.	15
	VC/RH	4,8,9	0.1	n.s.	6.1	ab	1.3	n.s.	11.1	b	1.2	a	19.9	bc	2.3	n.s.	12
	Weedy Check	10	0.0	n.s.	21.7	a	9.4	n.s.	32.0	a	2.4	a	65.4	a	3.5	n.s.	5
17-Jun	Conventional No-Till	1,2	0.2	c	1.5	b	0.5	c	3.8	b	0.2	b	6.2	d	0.4	c	6
Post	VC/RH + Herbicides	3	0.0	c	3.3	b	0.0	c	4.3	b	0.0	b	7.7	cd	1.0	bc	13
hoe	Burndown + Hoe	5	15.4	ab	20.3	a	16.7	b	20.3	a	4.0	ab	76.7	b	12.8	bc	17
	VC/RH + Hoe (Banded)	6	3.0	bc	13.3	a	14.4	b	14.3	a	1.7	ab	46.7	bc	18.3	bc	39
	VC/RH (Banded)	7	5.4	ab	21.7	a	22.7	ab	23.3	a	3.7	ab	76.7	b	28.3	bc	37
	VC/RH + Hoe	4,8	8.8	ab	20.7	a	21.2	ab	23.5	a	4.7	a	78.9	b	31.0	bc	39
	VC/RH	9	16.3	a	28.7	a	40.0	ab	33.0	a	8.7	a	126.7	a	84.3	a	67
	Weedy Check	10	11.7	ab	38.7	a	59.0	a	38.3	a	8.0	a	155.7	a	46.5	ab	30
16-Jul	Conventional No-Till	1	4.3	bc	7.4	bc	0.0	b	19.3	n.s.	1.7	bc	32.7	bc	2.0	b	6
Post	Herbicides + Cult	2	5.0	bc	7.3	c	4.0	b	10.0	n.s.	8.0	abc	34.3	bc	22.7	ab	66
cult	VC/RH + Herbicide	3	1.7	cd	1.7	d	0.0	b	9.7	n.s.	2.7	bc	15.6	c	1.0	b	6
	VC/RH + Hoe + Post	4	0.0	d	0.0	d	0.0	b	11.7	n.s.	0.3	c	12.0	c	1.7	b	14
	Burndown + Hoe + Cult	5	24.7	a	19.7	abc	25.3	a	22.7	n.s.	9.7	ab	102.0	a	70.4	a	69
	VC/RH + Hoe + Cult (Banded)	6	18.7	a	13.3	bc	27.7	a	18.3	n.s.	21.0	a	99.0	a	64.0	a	65
	VC/RH + Cult (Banded)	7	16.0	ab	11.3	bc	26.7	a	18.0	n.s.	12.3	ab	84.3	ab	44.0	ab	52
	VC/RH + Hoe + Cult	8	11.7	ab	16.0	abc	22.7	a	17.0	n.s.	7.7	ab	75.0	ab	74.3	a	99
	VC/RH + Cult	9	13.7	ab	24.4	ab	23.3	a	25.0	n.s.	7.7	abc	94.0	a	69.3	a	74
	Weedy Check	10	11.0	ab	34.4	a	25.0	a	12.4	n.s.	13.4	ab	96.1	a	40.7	ab	42

† Similar letters at a date within a column indicate no significant difference between treatments at p<0.05 (Tukey-Kramer mean separation test). n.s. indicate no statistical difference between treatments.

‡ Weed density from treatments that did not differ in at collection date were combined.

§ Others include all other weeds observed.

¶ Total is the summation of the four weeds and others.

Trt. No. = treatment number, AMARE = redroot pigweed, AMBEL = common ragweed, CHEAL = common lambsquarters, ERICA = horseweed, SETFA = giant foxtail, VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Table 2.8. Mean† weed density by corn treatment in 2009. Analyzed separately by dates, weed species, and subplot and resident areas.

Date	Treatment‡	Trt No.	Subplot: AMARE (Weed Density, Plants m^{-2})		AMBEL		CHEAL		SETFA		Other§		Total¶		Resident: Total		Percent of Subplot
28-Apr	Baseline	1-10	0.1		0.7		0.2		6.1		0.0		7.0		1.3		18
19-May	Conventional No-Till	1,2	0.0	n.s.	0.0	n.s.	0.0	n.s.	0.0	n.s.	0.1	n.s.	0.1	n.s.	0.1	n.s.	—
Post	VC/RH + Herbicides	3	0.0	n.s.	0.0	n.s.	0.0	n.s.	0.0	n.s.	0.0	n.s.	0.0	n.s.	0.0	n.s.	—
planting	Burndown	5	0.0	n.s.	0.0	n.s.	0.0	n.s.	0.0	n.s.	0.0	n.s.	0.0	n.s.	0.0	n.s.	—
	VC/RH (Banded)	6,7	0.0	n.s.	0.0	n.s.	0.0	n.s.	0.1	n.s.	0.0	n.s.	0.1	n.s.	0.7	n.s.	—
	VC/RH	4,8,9	0.0	n.s.	0.0	n.s.	0.0	n.s.	0.1	n.s.	0.1	n.s.	0.3	n.s.	0.0	n.s.	—
	Weedy Check	10	0.0	n.s.	0.0	n.s.	0.0	n.s.	0.3	n.s.	1.5	n.s.	1.8	n.s.	0.0	n.s.	—
12-Jun	Conventional No-Till	1,2	0.0	c	1.5	c	0.0	c	1.0	n.s.	1.0	d	3.5	d	0.6	c	18
Post	VC/RH + Herbicides	3	0.0	c	0.5	c	0.0	c	0.8	n.s.	1.0	d	2.3	d	0.5	c	22
hoe	Burndown + Hoe	5	120.8	ab	14.3	a	72.8	a	2.5	n.s.	38.0	abc	248.3	a	79.0	ab	32
	VC/RH + Hoe (Banded)	6	91.5	ab	6.3	abc	29.0	bc	2.3	n.s.	19.5	c	148.5	bc	70.8	abc	48
	VC/RH (Banded)	7	45.8	bc	5.5	bc	21.5	bc	1.0	n.s.	23.3	bc	97.0	c	59.5	bc	61
	VC/RH + Hoe	4,8	111.4	ab	12.5	ab	55.9	ab	4.5	n.s.	33.5	bc	217.8	ab	116.3	ab	53
	VC/RH	9	140.5	a	13.8	a	71.3	a	6.3	n.s.	54.8	a	286.5	a	158.5	a	55
	Weedy Check	10	147.5	a	13.0	ab	87.0	a	2.3	n.s.	42.8	ab	292.5	a	136.3	ab	47
2-Jul	Conventional No-Till	1	1.3	c	2.8	bcde	0.8	c	7.8	c	0.3	b	12.8	e	1.5	c	12
Post	Herbicides + Cult	2	1.8	c	1.3	de	0.3	c	5.8	c	0.8	b	9.8	e	5.3	bc	54
cult	VC/RH + Herbicide	3	0.3	c	2.5	cde	0.0	c	5.8	c	0.3	b	8.8	e	0.5	c	6
	VC/RH + Hoe + Post	4	0.3	c	0.3	e	0.0	c	24.5	ab	0.3	b	25.3	de	1.5	c	6
	Burndown + Hoe + Cult	5	44.8	ab	10.3	ab	27.5	ab	29.8	ab	3.5	ab	115.8	ab	38.0	a	33
	VC/RH + Hoe + Cult (Banded)	6	19.8	b	3.5	bcd	4.8	bc	12.5	bc	1.0	ab	41.5	cd	25.5	ab	61
	VC/RH + Cult (Banded)	7	21.0	b	4.3	bcd	2.5	c	15.5	abc	0.8	b	44.0	bcd	23.0	ab	52
	VC/RH + Hoe + Cult	8	36.0	ab	8.0	abc	13.8	b	28.8	ab	2.8	ab	89.3	abc	29.0	a	32
	VC/RH + Cult	9	39.8	ab	6.8	abc	19.5	ab	23.8	ab	3.5	ab	93.3	abc	53.0	a	57
	Weedy Check	10	87.3	a	15.5	a	52.3	a	51.0	a	6.0	a	212.0	a	94.8	a	45

† Similar letters at a date within a column indicate no significant difference between treatments at $p<0.05$ (Tukey-Kramer mean separation test). n.s. indicate no statistical difference between treatments.

‡ Weed density from treatments that did not differ in at collection date were combined

§ Others include all other weeds observed.

¶ Total equals the summation of the five weed species and others.

Trt. No. = treatment number, AMARE = redroot pigweed, AMBEL = common ragweed, CHEAL = common lambsquarters.

SETFA = giant foxtail, VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Table 2.9. ANOVA output for the effect of weed biomass on corn treatment, weed area, year, and interactions.

Effect	Num DF	Den DF	F Value	Pr > F
Year	1	90	19.92	<.0001
Treatment	9	27	53.53	<.0001
Weed Area	1	90	43.69	<.0001
Weed Area *Treatment	9	90	1.03	0.4213
Year*Treatment	9	90	2.24	0.0266
Year*Weed Area*Treatment	9	90	0.32	0.9649
Year*Weed Area	1	90	0.31	0.5779
2008				
Treatment	9	27	40.96	<.0001
Weed Area	1	30	67.49	<.0001
Treatment*Weed Area	9	30	7.68	<.0001
Subplot	9	27	41.81	<.0001
Resident	9	27	7.55	<.0001
2009				
Treatment	9	27	31.36	<.0001
Weed Area	1	30	24.50	<.0001
Treatment*Weed Area	9	30	3.57	0.004
Subplot	9	27	18.30	<.0001
Resident	9	27	32.79	<.0001

Table 2.10. Mean† weed biomass by corn treatment in 2008.

Treatment	Subplot												Resident		
	AMARE		AMBEL		CHEAL		SETFA		Other‡		Total§		Total		Percent of Subplot
	Weed Biomass (kg ha^{-1})														
Conventional No-Till	4	cd	221	bcd	0	c	112	ab	6	n.s.	343	d	26	b	7
Herbicides + Cult	24	bcd	55	cde	3	c	44	b	1	n.s.	127	d	40	b	32
VC/RH + Herbicide	14	cd	38	de	0	c	191	ab	44	n.s.	287	d	68	b	24
VC/RH + Hoe + Post	0	d	0	e	1	c	11	b	0	n.s.	11	d	1	b	11
Burndown + Hoe + Cult	500	a	2061	a	871	a	811	a	103	n.s.	4347	b	833	b	19
VC/RH + Hoe + Cult (Banded)	43	abcd	544	abc	188	b	423	a	108	n.s.	1306	d	269	b	21
VC/RH + Cult (Banded)	103	abc	990	ab	308	ab	509	a	1	n.s.	1910	cd	375	b	20
VC/RH + Hoe + Cult	257	ab	2135	a	820	ab	571	a	15	n.s.	3799	bc	2007	ab	53
VC/RH + Cult	305	ab	3783	a	856	a	335	a	12	n.s.	5292	b	1838	ab	35
Weedy Check	19	bcd	6691	a	2356	a	419	a	45	n.s.	9531	a	3931	a	41

† Similar letters in a column indicate no significant difference between treatments at p<0.05 (Tukey-Kramer mean separation test).

‡ Others include all other weeds observed.

§ Total equals the summation of the five weed species and others.

AMARE = redroot pigweed, AMBEL = common ragweed, CHEAL = common lambsquarters, ERICA = horseweed, SETFA = giant foxtail.

VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Table 2.11. Mean† weed biomass by corn treatment in 2009.

	Subplot												Resident		
Treatment	AMARE		AMBEL		CHEAL		SETFA		Other‡		Total§		Total		Percent of Subplot
	Weed Biomass (kg ha^{-1})														
Conventional No-Till	2	d	14	cd	0	d	19	cd	1	cd	35	c	5	d	14
Herbicides + Cult	1	d	1	d	0	d	4	d	8	abcd	13	c	5	d	35
VC/RH + Herbicide	0	d	40	bcd	0	d	23	bcd	0	d	63	c	104	d	164
VC/RH + Hoe + Post	0	d	0	d	0	d	17	cd	6	bcd	24	c	7	d	28
Burndown + Hoe + Cult	1062	abc	391	ab	276	ab	482	ab	162	a	2373	b	404	cd	17
VC/RH + Hoe + Cult (Banded)	150	bc	21	bcd	16	cd	197	abc	0	cd	384	c	111	d	29
VC/RH + Cult (Banded)	125	c	31	abcd	33	cd	187	abc	0	cd	376	c	197	d	52
VC/RH + Hoe + Cult	1218	abc	237	abc	90	bc	526	abc	297	abcd	2369	b	1053	c	44
VC/RH + Cult	1826	ab	279	ab	425	ab	753	a	109	ab	3392	ab	2238	b	66
Weedy Check	2320	a	439	a	527	ab	1033	a	163	abc	4481	a	3507	a	78

† Similar letters in a column indicate no significant difference between treatments at $p<0.05$ (Tukey-Kramer mean separation test).

‡ Others include all other weeds observed.

§ Total equals the summation of the five weed species and others.

AMARE = redroot pigweed, AMBEL = common ragweed, CHEAL = common lambsquarters, SETFA = giant foxtail.

VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Table 2.12. ANOVA output for the effect of corn yield on treatment, weed area, year, and interactions.

Effect	Num DF	Den DF	F Value	Pr > F
Year	1	89	809.87	<.0001
Treatment	9	27	30.82	<.0001
Weed Area	1	89	15.45	0.0002
Weed Area*Treatment	9	89	3.27	0.0017
Year*Treatment	9	89	8.63	<.0001
Year*Weed Area*Treatment	9	89	1.77	0.0846
Year*Weed Area	1	89	18.80	<.0001
2008				
Treatment	1	29	57.35	<.0001
Weed Area	9	27	22.89	<.0001
Treatment*Weed Area	9	29	7.31	<.0001
Subplot	9	26	21.96	<.0001
Resident	9	27	9.41	<.0001
2009				
Treatment	9	27	9.12	<.0001
Weed Area	1	30	0.19	0.6629
Treatment*Weed Area	9	30	1.78	0.1134
Subplot	—	—	—	—
Resident	—	—	—	—

Table 2.13. Mean† corn grain yield by treatment in 2008 and 2009.

Treatment	2008				2009‡	
	Subplot		Resident			
	Grain Yield (kg ha^{-1})					
Conventional No-Till	10017	a	9506	ab	13206	ab
Herbicides + Cult	9622	a	9448	ab	12359	ab
VC/RH + Herbicides	9754	a	9563	ab	13266	a
VC/RH + Hoe + Post	9384	a	9882	a	12406	ab
Burndown + Hoe + Cult	5846	bc	8600	abc	12161	ab
VC/RH + Hoe + Cult (Banded)	7847	ab	8774	abc	12197	ab
VC/RH + Cult (Banded)	7736	ab	8843	abc	12638	ab
VC/RH + Hoe + Cult	5249	bc	7308	bcd	12005	b
VC/RH + Cult	4323	cd	7060	cd	11980	b
Weedy Check	1494	d	5336	d	10507	c

† Similar letters in a column indicate no significant difference between treatments at $p<0.05$ (Tukey-Kramer mean separation test).

‡ Corn grain yield for 2009 was pooled due to no significant difference in subplot and resident yields and no treatment*area interaction.

VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Table 2.14. Weed control cost, total production cost, and breakeven price by corn treatment in 2008.

Treatment	Weed Control Cost ($ ha^{-1})				Total Production Cost† ($ ha^{-1})		Breakeven Price ($ kg^{-1})	
	Herbicide Cost	Machinery Cost	Labor Cost	Total	Subplot	Resident	Subplot	Resident
Conventional No-Till	138.77	5.66	1.56	145.99	1067.82	1065.59	0.107	0.112
Herbicides + Cult	138.77	26.29	5.02	170.08	1090.60	1090.11	0.113	0.115
VC/RH + Herbicide	99.83	41.17	10.11	151.10	1071.10	1110.91	0.110	0.116
VC/RH + Hoe + Post	83.84	55.33	17.37	156.54	1074.66	1076.39	0.115	0.109
Burndown + Hoe + Cult	38.94	40.45	12.28	91.68	993.73	1004.68	0.170	0.117
VC/RH + Hoe + Cult (Banded)	39.96	73.64	19.27	132.87	1043.80	1047.53	0.133	0.119
VC/RH + Cult (Banded)	39.96	59.48	12.01	111.44	1021.34	1025.81	0.132	0.116
VC/RH + Hoe + Cult	0.00	70.30	19.27	89.58	988.64	996.60	0.188	0.136
VC/RH + Cult	0.00	56.14	12.01	68.15	962.94	973.64	0.223	0.138
Weedy Check	0.00	0.00	0.00	0.00	882.17	897.34	0.590	0.168

†Includes all production costs except for land and management charges.

VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Table 2.15. Weed control cost, total production cost, and breakeven price by corn treatment in 2009†.

Treatment†	Weed Control Cost ($ ha^{-1})				Total Production Cost ‡ ($ ha^{-1})	Breakeven Price ($ kg^{-1})
	Herbicide Cost	Machinery Cost	Labor Cost	Total		
Conventional No-Till	138.77	5.66	1.56	145.99	1080.25	0.082
Herbicides + Cult	138.77	46.93	8.48	194.18	1126.03	0.091
VC/RH + Herbicide	99.83	31.88	7.68	139.39	1072.96	0.081
VC/RH + Hoe + Post	83.84	41.32	12.53	137.69	1067.25	0.086
Burndown + Hoe + Cult	38.94	56.36	13.32	108.63	1036.06	0.085
VC/RH + Hoe + Cult (Banded)	39.96	80.26	17.89	138.11	1066.11	0.087
VC/RH + Cult (Banded)	39.96	70.82	13.05	123.82	1053.19	0.083
VC/RH + Hoe + Cult	0.00	76.92	17.89	94.81	1020.40	0.085
VC/RH + Cult	0.00	67.48	13.05	80.53	1005.72	0.084
Weedy Check	0.00	0.00	0.00	0.00	917.72	0.087

† Subplot and resident results were pooled due to no significant difference in subplot and resident yields and no yield treatment*area interaction.

‡ Includes all production costs except for land and management charges.

VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Table 2.16. Net returns† by treatment at select corn prices in 2008.

Treatment	Price of Corn ($ kg^{-1}) 0.138 Subplot	0.138 Resident	0.157 Subplot	0.157 Resident	0.177 Subplot	0.177 Resident	0.197 Subplot	0.197 Resident
	Returns above total cost ($ ha^{-1})							
Conventional No-Till	312	244	509	431	707	618	904	805
Herbicides + Cult	235	212	425	398	614	584	803	770
VC/RH + Herbicide	273	207	465	395	657	583	849	771
VC/RH + Hoe + Post	210	277	395	471	579	666	764	860
Burndown + Hoe + Cult	-197	172	-82	341	33	510	149	680
VC/RH + Hoe + Cult (Banded)	29	153	183	326	338	498	492	671
VC/RH + Cult (Banded)	45	193	197	367	349	541	501	715
VC/RH + Hoe + Cult	-274	2	-171	146	-67	290	36	434
VC/RH + Cult	-367	-1	-282	138	-197	277	-112	416
Weedy Check	-676	-162	-647	-57	-617	48	-588	153

† Includes all production costs except for land and management charges.

VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Table 2.17. Net returns† by treatment at select corn prices in 2009‡.

Treatment	Price of Corn ($ kg^{-1})			
	0.138	0.157	0.177	0.197
	Returns above total cost ($ ha^{-1})			
Conventional No-Till	739	999	1259	1519
Herbicides + Cult	577	820	1063	1307
VC/RH + Herbicide	755	1016	1277	1538
VC/RH + Hoe + Post	636	881	1125	1369
Burndown + Hoe + Cult	634	873	1113	1352
VC/RH + Hoe + Cult (Banded)	609	849	1089	1329
VC/RH + Cult (Banded)	688	937	1186	1434
VC/RH + Hoe + Cult	628	864	1101	1337
VC/RH + Cult	645	881	1117	1352
Weedy Check	530	737	944	1150

† Includes all production costs except for land and management charges.

‡ Subplot and resident results were pooled due to no significant difference in subplot and resident yields and no treatment*area interaction.

VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

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Chapter 3

Integrated Mechanical Weed Management in High Residue Soybean Systems

Abstract

The objective of this research was to evaluate the potential of select mechanical tillage implements and reduced herbicide inputs in integrated high residue soybean systems. This integrated approach attempted to reduce the negative effects from herbicides and intense inversion tillage, while providing effective economical weed control. Treatments examined a vertical coulter, a rotary harrow, a high-residue rotary hoe, and a high-residue row cultivator in combination with soil-applied broadcast, soil-applied banded, or post-emergence herbicides. Conventional no-till using herbicides and a weedy check were included for comparison and the weed seed bank was supplemented to help ensure an effective assessment. Evaluation parameters included crop population, weed density, end of season weed biomass, surface residue, grain yield, and costs.

Weed severity and production year influenced the efficacy of the mechanical implements. Treatments including herbicides reduced weed density and weed biomass compared to treatments relying on mechanical control alone. The vertical coulter and rotary harrow did not provide the weed control of a herbicide burndown. While the rotary hoe had a minimal impact on surface residue, weed densities were higher than with the soil-applied broadcast herbicide treatments, but provided 41 to 52% control under higher weed severity. However, the rotary hoe did not increase weed control in banded herbicide treatments. Treatments that included banded herbicide tended to have better weed control than treatments that relied strictly on mechanical implements, but lower weed control than broadcast herbicides. Of the mechanical tools tested, the high residue cultivator was the most effective in reducing weed density and weed biomass, while maintaining crop yield. The greater reliance on mechanical implements reduced weed control cost, but tended to have higher breakeven prices due to lower yields. Overall, mechanical tillage implements alone did not provide adequate weed control, while integration with reduced herbicide inputs maintained acceptable weed control and competitive crop yields.

Nomenclature: Soybean, *Glycine max* L.; giant foxtail, *Setaria faberi* Herrm.; common lambsquarters, *Chenopodium album* L.; redroot pigweed, *Amaranthus retroflexus* L.; horseweed *Conyza Canadensis* L.; common ragweed, *Ambrosia artemisiifolia* L.;

Key Words: integrated weed management, mechanical weed control, conservation tillage, vertical coulter, rotary harrow, high residue rotary hoe, high residue cultivator, banded herbicides

As discussed in chapter 1, the development of glyphosate-resistant soybean has facilitated the adoption of no-till and reduced the use of some soil residual herbicides that can impact water quality herbicides (Gilliom, 2007). However at the same time, this technology has greatly increased the use of glyphosate (NASS, 2009). Sole reliance on glyphosate to control weeds in soybean almost assures that glyphosate-resistant weed communities of multiple weed species will be widespread in the near future. As such, alternative control options to reduce the reliance on glyphosate, as well as control resistant weeds, need to be developed.

With effective herbicides, producers can take advantage of the benefits of narrow row soybean. There is generally a yield benefit for soybean planted in narrow rows (Bullock et al., 1998; Grau et al., 1994; Lueschen et al., 1992; Oplinger and Philbrook, 1992), although results can vary with cultivar (Grau et al., 1994), location (Lueschen et al., 1992) and planting date (Oplinger and Philbrook, 1992). Hock et al. (2006) compared 76-cm rows to 19-cm rows and reported that soybean canopy closure occurred 20 days earlier with the narrow rows. Earlier canopy closure in narrow rows can result in less weed emergence and competition than wide row soybean (Mulugeta and Boerboom, 2000). However, if herbicide-resistant weeds become problematic, alternative herbicides or alternative control strategies must be considered. As an example, a shift to wide rows to facilitate cultivation may be a solution.

Although herbicides are generally an important component for managing weeds in high residue systems, as discussed in chapter 2 there are tools that can help reduce reliance on herbicides, thereby reducing the threat for herbicide-resistant weeds. While little objective information exists to support the use of these tools, the results appear encouraging. Hooker et al. (1997) reported that compared to broadcast herbicides, banded herbicide plus cultivation can provide similar weed control and soybean yield. In reduced tillage systems, adoption of banded herbicides can reduce weed control cost which in return can increase or maintain net returns (Cox et al., 1999; Mulder and Doll, 1993; Poston et al., 1992) and similar results could be found in conservation systems.

The objective of this study was to develop integrated weed management systems for high residue soybean that are less reliant on herbicides to reduce off-site movement and/or select for herbicide-resistant weeds. Specifically, this study evaluated: 1) combinations of mechanical tools with and without herbicides for weed management in high residue soybean, 2) the impact of these management systems on surface residue cover, and 3) the production costs, breakeven price, and net returns of the management systems in soybean.

Based on these objectives, we developed four hypotheses: 1) the combination of the vertical coulter/rotary harrow would provide the weed control of a burndown herbicide while maintaining the residue level of a no-till system, 2) two to three passes of the rotary hoe would provide the weed control comparable to a soil-applied residual herbicide, while maintaining surface residue, 3) the inter-row cultivator would provide between-row weed control equivalent to soil-applied and post-emergence herbicides while maintaining residue, and 4) banded soil-applied herbicide at planting would provide improved weed control over the cultivator alone by providing in-row weed control, while the cultivator provides between-row weed control. With this integrated weed management approach, the benefits of conservation tillage in conjunction with limited herbicide use will help achieve more sustainable weed management systems. This research is anticipated to help producers who desire to reduce herbicide inputs while still minimizing soil erosion potential on their farm.

Material and Methods

The research was conducted on The Pennsylvania State University Agronomy Farm at the Russell E. Larson Agricultural Research Center, located 16 kilometers southwest of State College, Pennsylvania (Latitude: 40° 43' N Longitude: 77° 56' W). The soils were predominately Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalf) in 2008 and Murrill channery silt loam (Fine-loamy, mixed, semiactive, mesic Typic Hapludults) in 2009 with slopes varying from 0-3%. The Hagerstown series consists of deep, well drained soils that formed in limestone residuum (Braker, 1981). The Murrill series consists of deep, well drained soils formed in sandstones colluviums and underlying residuum weathered from limestone (Braker, 1981). Rainfall data was collected from local weather stations and temperature data was obtained from ZedX[1] using interpolated data from local weather stations. Cumulative growing degree days (GDD) from April 1 to harvest were calculated using base 10 °C and max 30 °C.

The study contained ten treatments and individual plots were 30-m long and 4.6-m wide consisting of soybean planted in 76- or 19-cm wide rows. Treatments including the cultivator were planted in 76-cm wide rows to facilitate operation of the cultivator. The weedy check was also planted in 76-cm wide rows. The study was conducted in a field that was corn grain the previous year and the stalks were shredded in the fall. In 2008, Schillinger[2] ‘367.RC’ soybean seed treated with thiamethoxam {3-[(2-chloro-5-thiazolyl)methyl]tetrahydro-5-methyl-*N*-nitro-4*H*-1,3,5-oxadiazin-4-imine} and in 2009, Asgrow[3] ‘3603’ soybean seed treated with mefenoxam [methyl *N*-(2,6-dimethylphenyl)-*N*-(methoxyacetyl)-D-alaninate] and fludioxonil [4-

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[1] ZedX Inc., 369 Rolling Ridge Drive, Bellefonte, PA 16823
[2] Schillinger Seed, Inc, 4200 Corporate Drive, Suite 106, West Des Moines, IA 50266
[3] Asgrow is a product of Monsanto Company, 800 N. Lindbergh Blvd., St. Louis, MO 63167

(2,2-difluoro-1,3-benzodioxol-4-yl)-1*H*-pyrrole-3-carbonitrile] was used in the study. Cultivars were glyphosate [*N*-(phosphonomethyl)glycine] resistant (event 40-3-2) and inoculated with *Bradyrhizobium japonicum.* Treatments seeded in 19-cm rows were planted at 494,193 plants hectare^{-1} with a Great Plains[4] no-till drill. Treatments seeded in 76-cm rows were planted at 432,419 plants hectare^{-1} with a John Deere[5] 1780 no-till planter equipped with Dawn[6] row cleaners.

Weed Populations

Weed populations were a supplemental weed seed bank (here after referred to as the subplot) and the existing weed seed bank (resident). Weed seeds were sown by hand in subplots in the late fall of each year in a 1.5 by 3 m band in the center of each plot (referred to as subplot). A mixture of 1500 seeds m^{-2} each giant foxtail (*Setaria faberi* Herrm., #[7] SETFA), common lambsquarters (*Chenopodium album* L., # CHEAL) redroot pigweed (*Amaranthus retroflexus* L., # AMARE), and horseweed (*Conyza Canadensis* L.,# ERICA) and 750 seeds m^{-2} common ragweed (*Ambrosia artemisiifolia* L., # AMBEL) was broadcast in the subplot area to ensure an adequate population to effectively evaluate weed control. These species are common in the region and the weed seeds were collected from local populations.

Weed Control

Burndown, broadcast soil-applied, and post-emergence herbicides were applied using a tractor mounted sprayer. The burndown application consisted of 0.84 kg ae ha^{-1} glyphosate.

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[4] Great Plains Mfg Inc., 1525 E. North Street, Salina, Kansas 67401
[5] Deere & Company, One John Deere Place, Moline, IL 61265
[6] Dawn Equipment, P.O. Box 497, Sycamore, IL 60178
[7] Letters following this symbol are a Weed Science Society of America-approved computer code.

The soil-applied broadcast and banded herbicides included 1.42 kg ai ha^{-1} s-metolachlor {2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-[(1*S*)-2-methoxy-1-methylethyl]acetamide}, 0.224 kg ai ha^{-1} metribuzin [4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one], and 0.039 kg ai ha^{-1} chlorimuron {2-[[[[(4-chloro-6-methoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]benzoic acid}. The planter was equipped with a small plot sprayer for application of banded soil-applied herbicide. The herbicide was applied in a 30-cm band using flat fan 4002E TeeJet®[8] tips positioned directly behind the planter units. Post-emergence herbicides consisted of 0.84 kg ae ha^{-1} glyphosate. All herbicides were applied in water at 187 L ha^{-1} at 207 kPa.

The vertical coulter/rotary harrow, rotary hoe, and cultivator were substituted for a burndown, soil-applied residual, and post-emergence herbicides, respectively. The vertical coulter used in this study was constructed on a modified chisel plow frame using Yetter[9] vertical tillage attachments spaced 23 cm apart and operated at 11.3 kilometers per hour (kph) (Figure 2.2). Water-filled barrels attached to the frame added about an additional 500 kg of weight to increase penetration. The rotary harrow used in this study was a prototype tool developed by Phoenix Rotary Equipment[10] and was operated at 16.1 kph. The prototype in this study had two sets of gangs (rather than a single set) designed to increase the activity of the implement in no-till systems in a single pass. In 2008, an early April operation (Table 3.2) of the vertical coulter/rotary harrow was performed in certain treatments. Prior to planting in May, a second rotary harrow operation was made to the same treatments. In contrast, a single vertical

[8] Spraying System Company, P.O. Box 7900 Wheaton, IL 60187
[9] Yetter Manufacturing, Inc, PO Box 358 109 S. McDonough, Colchester, IL 62326
[10] Phoenix Rotary Equipment, 33908 128th Street County Road 4, Waseca, MN 56093

coulter/rotary harrow operation was performed prior to planting in May in 2009. The high residue rotary hoe used was a 4.6 meter M & W[11] 1815MT operated at 16.1 kph with 272 kg of weight added to increase penetration. The high residue cultivator was a 6-row John Deere 886 equipped with 41-cm wide sweeps, disk hillers, and a Sukup Auto Guide®[12] guidance system operated at 11.3 kph. The guidance system allowed for a faster operating speed and reduces crop injury due to operator error. The cultivator's disk hillers were set at 5-10 degrees and 11-14 cm away from soybean plants to pull soil and residue from the row. For the second cultivation, the disk hillers were removed. Rotary hoe and cultivator operations were based on soil moisture conditions and emerged weed size or potential for weed emergence and were performed when the implements would be most effective. In 2008, there were three rotary hoe operations compared to two rotary hoe operations in 2009. Wet weather in 2009 prevented a third rotary hoe operation.

Data Collection

Timing of data collection is reported in Table 3.2. Soybean population was determined in each plot after completing all weed control operations by counting soybean plants in the center two rows in the 76-cm rows and 4 rows in the 19-cm rows for a length of 5.3 m. Surface residue from the previous corn crop and weed density measurements were collected before any mechanical operation in the spring and following the first vertical coulter/rotary harrow (2008 only), planting, final rotary hoe, and final cultivator operation. The measurements were collected just prior to the next operation and included only corn residue. Residue was

[11] M & W Gear Company, 10205 Sangamon Avenue, Gibson City, IL 60936
[12] Sukup Manufacturing Company, 1555 255th Street, Sheffield, IA 50475

measured using the line-transect method (Shelton et al., 1997). Weed density was estimated using 0.25 m^2 quadrats with four 0.25 m^2 quadrats per plot within the subplot and from the resident weed population. In 2008, three 0.25 m^2 quadrats rather than four were sampled within the subplot for the initial weed count, but all following counts included four quadrats. Weed biomass was estimated in late summer from each plot by harvesting the above-ground weed plant material from a 0.76 by 3.0 m area within the subplot and from two 0.76 by 3.0 m areas within the resident population. The samples were separated by weed species, oven dried at 55 C for at least 72 hours and weighed. Soybean grain yield was harvested using a small plot combine to harvest the center 1.5 m within each plot. Soybean within the subplot and resident weed areas were harvested separately. The grain was weighed and corrected to 130 g kg^{-1} moisture content.

Data Analysis

Each of the ten treatments was replicated four times in a randomized complete block design. All data were analyzed with PROC MIXED in SAS (SAS, 2009). Means were separated using the Tukey-Kramer test at $P < 0.05$ to determine significant differences. A split-plot fixed effects model was used with treatment (main plot), subplot and resident weed area (split-plot), and the interaction between the two factors as fixed effect terms, with block and the treatment by block interaction as random effects. When the treatment by weed area interaction was significant, the weed areas (subplot and resident) were analyzed separately. When treatments were not different at specific data collection periods, the treatment data was combined to reflect only relevant treatments. Weed density data and individual weed species for weed biomass were log transformed ($\log_{10} x + 1$) as needed to reduce heterogeneity of variance and non-transformed data is presented.

Economic Analysis

Enterprise budgets were computed to provide an economic comparison of treatments. Enterprise budgets provide an estimate of the potential revenue, expenses, and profit for a single enterprise and can be used to compare potential alternative enterprises (Kay et al., 2008). Enterprise budgets were calculated for each treatment using the Mississippi State Budget Generator v6.0 (Laughlin and Spurlock, 2008). Tractors and implements sizes are based on typical size for mixed crop and livestock farms of the Mid-Atlantic region. Production costs were based on 2009 data obtained as noted in Tables 3.3 and 3.4. A 7% interest rate for opportunity cost was charged from the date of operation or use of input until harvest. Land and management charges were not included in total production cost. Weed control costs were separated from total production cost and then further separated into herbicide, machinery, and labor cost for each treatment. Total production costs and the mean treatment yields were used to calculate breakeven prices. Breakeven price provides the minimum price needed to cover total production cost at a given yield and is calculated by dividing the total production cost by the treatment yield (Kay et al., 2008). In addition, net returns provide an estimate of returns above total cost and were calculated by multiplying treatment yields by an expected corn price and subtracting total production cost (Kay et al., 2008). Net returns assuming soybean prices of \$0.330 kg^{-1}, \$0.367 kg^{-1}, \$0.403 kg^{-1}, and \$0.440 kg^{-1} are presented. The range of prices was used to evaluate the sensitivity of changes in price on the profitability of the treatments.

Results

Climatic Conditions

Total rainfall from April 1 through November was 550 mm in 2008 (NRCS, 2008) and 575 mm in 2009 (EPA, 2009) (Table 2.5). The historical average total rainfall from April 1 through November is 713 mm (NCDC, 2009)(Table 2.5). Cumulative GDD from April 1 to harvest was 1512 in 2008 and 1499 in 2009(Figure 2.2). The 30-year historical average GDD for the time period is 1537.

Soybean Population

The 2008 and 2009 soybean populations were analyzed separately due to differences between years. In 2008, the average population was 40% and 50% of the seeding rate for the 18-cm and 76-cm rows. In contrast, in 2009 the average population was 80% and 86% of the seeding rate for the 18-cm and 76-cm rows. In 2008, there was no difference in soybean populations across all treatments (Figure 3.1). Although not significantly different, the population averaged 198,802 plants ha^{-1} in the 19-cm rows and 217,962 plants ha^{-1} in the 76-cm rows. In 2009, soybean populations were higher than in 2008 and again there was no difference in soybean populations across all treatments, but row spacing was significant. The 19-cm row spacing treatments averaged 395,237 plants ha^{-1} whereas the 76-cm rows treatments averaged 370,247 plants ha^{-1}. In general, the implements did not affect soybean populations.

Residue

Residue data was separated by years due to differences in the number of mechanical weed control operations within years. In 2008, surface residue cover averaged 84% across the experimental site prior to any tillage or planting operations on April 8 (Table 3.5). After soybean planting, residue cover in the vertical coulter/rotary harrow was 16 percentage points lower (49 vs. 65%) than in the no-till. After three rotary hoe operations, there was no evidence the rotary hoe impacted residue cover. The no-till and rotary hoe operation alone averaged 57%, whereas the vertical coulter/rotary harrow with and without the rotary hoe averaged 43% residue cover on June 26. Residue cover across treatments receiving two passes with the cultivator averaged 13%, compared to 45% in the no-till and 29% in the vertical coulter/rotary harrow with and without the rotary hoe (July 17).

In 2009, the previous corn crop residue was less than in 2008, averaging 47% across the experimental site prior to any tillage or planting operations on May 18 (Table 3.5). After soybean planting, residue cover in the vertical coulter/rotary harrow treatments was 7 percentage points lower (33 vs. 40%) than the no-till treatments (June 1). After two rotary hoe operations, there was no evidence the three rotary hoe operations impacted residue cover (June 25). The no-till averaged the highest with 37%, whereas the vertical coulter/rotary harrow + rotary hoe averaged the lowest with 28% residue cover. Residue cover across treatments with two passes with the cultivator averaged 19%, compared to 31% in the no-till and 25% in the vertical coulter/rotary harrow with and without the rotary hoe (July 14).

Weed Density

Weed data was separated by years due to differences in the number of mechanical weed control operations within years and timing of data collection. In 2008, prior to the first vertical coulter/rotary harrow operation, no weeds were present (April 8; Table 3.6). On May 13 following the first vertical coulter/rotary harrow the average weed density ranged from 16 to 29 plants m^{-2} with giant foxtail comprising 61% of the total weed density. The vertical coulter and rotary harrow had 46% more weeds then the weedy check. Following planting and some additional weed management treatments (vertical coulter/rotary harrow, burndown, and soil-applied herbicides) on May 21, there was no difference in weed density among the treatments and the average weed density was 4 plants m^{-2} with the “other” weed group representing 48% of the total weed density. On June 25, after the rotary hoe operations were complete, weed densities ranged from 7 to 110 plants m^{-2} in the subplot, with giant foxtail representing 57% of the total weed density. Treatments with the broadcast soil-applied herbicide had the lowest weed density, with an average less than 14 plants m^{-2}. In contrast, treatments that included the rotary hoe or banded herbicides ranged from 29 to 64 plants $m^{-2,}$ whereas treatments without the rotary hoe or soil-applied herbicides ranging from 86 to 110 plants m^{-2}. Compared to the vertical coulter/rotary harrow treatment, the vertical coulter/rotary harrow + rotary hoe reduced weeds by 41% and banded herbicides reduced weed density by 49%. Conversely, the rotary hoe did not reduce weed density when a banded soil-applied herbicide was included. By July 25, after cultivation and post herbicide applications had been completed, weed densities ranged from 5 to 117 plants m^{-2} in the subplot, with common lambsquarters and giant foxtail comprising 17 and 44% of the total emerged weeds. Weed densities in treatments including cultivation with banded herbicides or post-emergence herbicides averaged less than 20 plants m^{-2}. In contrast, treatments with cultivation and no soil-applied herbicide ranged from 32 to 55 plants m^{-2} and treatments without cultivation, or post-emergence herbicides ranged from 72 to 117 plants m^{-2}. Weed emergence trends among the treatments in the resident weed areas were generally similar to those in the subplots, although weed density was on average 73% lower in the resident plots compared to the subplots, depending on the sampling dates and treatment. In addition, there were no treatment differences between the subplot and resident populations on May 13 and June 21 and on June 25 neither the rotary hoe nor banded herbicides reduced weed density.

In 2009, weed density averaged 49 plants m^{-2} prior to mechanical operations, with giant foxtail comprising 57% of the total weed density on May 20 (Table 3.7). By June 1, following planting and some of the management treatments (vertical coulter/rotary harrow, burndown, and soil-applied herbicides), average weed density ranged from 2 to 61 plants m^{-2}, with giant foxtail representing 40% of the total weed density. Treatments that included a burndown herbicide application had less than 5 plants m^{-2}, whereas the average weed density in treatments with the vertical coulter/rotary harrow ranged from 16 to 20 plants m^{-2} and the weedy check averaged 61 plants m^{-2}. By June 24 when all the rotary hoe operations had been completed, average weed density ranged from 4 to 177 plants m^{-2}, with giant foxtail representing 53% of the total. Treatments with the broadcast soil-applied herbicide had the lowest weed density, averaging less than 20 plants m^{-2}. In contrast, weed density in treatments including the rotary hoe or banded herbicides ranged from 23 to 92 plants m^{-2}, whereas treatments without the rotary hoe or soil-applied herbicides ranging from 130 to 177 plants m^{-2}. Compared to the vertical coulter/rotary harrow treatment, the vertical coulter/rotary harrow + rotary hoe reduced weeds by 52% and banded herbicides reduced weed density 69%. Conversely, the rotary hoe did not reduce weed density when a banded soil-applied herbicide was included. By July 14 after cultivation and post herbicide applications had been completed, average weed density ranged from 2 to 171 plants m^{-2}, with common lambsquarters and giant foxtail comprising 18 and 45% of the total emerged weeds. Weed density in treatments including cultivation with banded herbicides or post-emergence herbicides averaged less than 15 plants m^{-2}, whereas treatments with cultivation but without banded herbicide ranged from 34 to 46 plants m^{-2}. Treatments without cultivation or post-emergence herbicides ranged from 139 to 171 plants m^{-2}. Weed emergence trends among the treatments in the resident weed areas were generally similar to those in the subplots, although weed density was 79% lower in the resident plots compared to the subplots, depending on the sampling dates and treatment. On June 24 in the resident weed population, the rotary hoe did not reduce weed densities while banded herbicides reduced weed density on average 75%.

Weed Biomass

Subplot weed biomass was affected by weed management treatment, but the precise nature of this effect depended on the study year (Table 3.8). In the 2008, weed biomass ranged from 82 to 4206 kg ha^{-1} in the subplots and from 7 to 1738 kg ha^{-1} in the resident plot areas (Table 3.9). In the subplots, giant foxtail and common ragweed were the most abundant weeds, comprising 32 and 42% of total weed biomass. Average weed biomass in treatments that included a post-emergence herbicides or cultivation with banded herbicide was less than 800 kg ha^{-1}, whereas weed biomass in all the other treatments ranged from 2591 to 4206 kg ha^{-1}. Differences in weed biomass among the treatments in the resident plot areas were generally similar to those in the subplots, although when averaged across treatments, resident weed biomass was 72% lower than the subplot weed biomass. While treatment results were similar for the subplot, the vertical coulter/rotary harrow + cultivator and the vertical coulter/rotary harrow + rotary hoe + cultivator reduced weed biomass 56 and 52%, compared to the weedy check in the resident weed population.

In 2009 weed areas were pooled as a result of no significant weed area by treatment interaction (Table 3.8) and weed biomass ranged from 2 to 7512 kg ha^{-1}, with common ragweed, common lambsquarters and horseweed comprising 17, 25, and 38% of the total weed biomass, respectively (Table 3.10). Average weed biomass in treatments that included post-emergence herbicides was less than 17 kg ha^{-1}, whereas treatments including cultivation with banded herbicide averaged 719 kg ha^{-1}. In contrast, weed biomass in treatments with cultivation, but without banded herbicide ranged from 1223 to 1902 kg ha^{-1} and the vertical coulter/rotary harrow + rotary hoe and the weedy check averaged 3558 and 7512 kg ha^{-1}. Compared to a similar treatment without banded herbicides, banded herbicides reduced weed biomass 59%, and compared to the weedy check, the vertical coulter/rotary harrow + cultivator and the vertical coulter/rotary harrow + rotary hoe + cultivator reduced weed biomass 78 and 75%, respectively.

Soybean Yield

Soybean grain yield was affected by the weed management treatments, but the specific nature of this effect was dependent on the study year (Table 3.11). In 2008, average soybean yields ranged from 1055 to 2676 kg ha^{-1} in the subplot and 1893 to 2661 kg ha^{-1} in the resident weed population (Table 3.12). In the subplot, average soybean yields in treatments that included a post-emergence herbicides or cultivation with banded herbicide ranged from 2011 to 2676 kg ha^{-1}, whereas soybean yields in all other treatments ranged from 1055 to 1515 kg ha^{-1}. Differences in soybean yield within the resident weed areas were generally similar to those in the subplots, although soybean yield in the resident area tended to be higher than the subplot, particularly when herbicide use decreased.

In 2009, average soybean yields ranged from 1584 to 3603 kg ha^{-1} in the subplots and 2781 to 3625 kg ha^{-1} in the resident weed areas (Table 3.12). In the subplot, average soybean yields in treatments that included a post-emergence herbicides or cultivation ranged from 2887 to 3625 kg ha^{-1}, whereas soybean yields in the vertical coulter/rotary harrow + rotary hoe and weedy check averaged 1584 and 2141 kg ha^{-1}. The weedy check and vertical coulter/rotary harrow + rotary hoe had significantly lower yields than the other treatments. Differences in soybean yield within the resident weed areas were generally similar to those in the subplots and soybean yield in the resident area tended to be similar to the subplot with the exception of the weedy check and the vertical coulter/rotary harrow which were higher.

Production Costs

Differences in total production cost between years were a result of differences in weed control costs (Tables 3.13 and 3.14). All other costs were held constant with \$353 ha^{-1} charged to all 76-cm treatments and \$369 to all 19-cm treatments which included seed, planting, and harvesting. Cost differences between row spacing were a result of differences in planter and drill operational cost along with higher seeding rates in the drill treatments. In 2008, treatments total weed control cost ranged from \$0 to \$195 ha^{-1} and with less reliance on herbicides herbicide cost decreased from \$149 ha^{-1}, while machinery and labor cost increased up to \$111 ha^{-1} and \$26 ha^{-1}, respectively (Table 3.13). In 2009, total weed control cost ranged from \$0 to \$163 ha^{-1} and herbicide cost decreased from \$149 ha^{-1}, while machinery and labor costs increased up to \$80 ha^{-1} and \$18 ha^{-1}, respectively with less reliance on herbicides (Table 3.14). Two passes with the vertical coulter/rotary harrow + herbicides was the most expensive weed control program in 2008 at \$195 ha^{-1} and the conventional no-till treatment was the most expensive in 2009 at \$163 ha^{-1}. Of the mechanical treatments, the vertical coulter/rotary harrow + rotary hoe treatment was the least expensive in both years. One pass of the vertical coulter/rotary harrow cost about \$8 ha^{-1} less than a glyphosate burndown application (Tables 3.3 and 3.4). The rotary hoe was the least expensive weed control tool around \$7 ha^{-1} per pass, but two to three passes were utilized in this experiment. Three passes with the rotary hoe cost less than a soil-applied broadcast, but more than banded soil-applied herbicides. Two passes of the cultivator cost about \$8 ha^{-1} more than the post-emergence herbicide. The combination of banded herbicide plus two passes with the cultivator cost \$49 ha^{-1} less than the combination of soil-applied broadcast and post-emergence herbicides. The use of the auto guide system on the cultivator increased the initial cost of the cultivator by \$6,000, but the cost was reduced by \$14.93 ha^{-1} as a result of the increase in speed which primarily reduced labor costs. The sprayer system for banding herbicide on the planter increased the cost of the planter \$3.33 ha^{-1}, but by reducing the amount of herbicide applied by 60% through banding, the cost of the soil residual herbicide was reduced proportionately by 60%.

Although total production costs were similar between years, the higher yields in 2009 resulted in lower breakeven prices compared to 2008. Treatments total production cost ranged from \$353 to \$569 ha^{-1} in 2008 (Table 3.13) and from \$353 to \$537 ha^{-1} in 2009 (Table 3.14). In 2008, breakeven prices ranged from \$0.186 to \$0.399 kg^{-1}, but only ranged from \$0.135 to \$0.223 kg^{-1} in 2009. In 2008, the vertical coulter/rotary harrow + rotary hoe + post-emergence herbicide had the lowest breakeven soybean price at \$0.186 kg^{-1} and the vertical coulter/rotary harrow + rotary hoe the highest at \$0.399 kg^{-1}. The greater reliance on mechanical weed control tools resulted in the lower yields which increased the breakeven prices. In 2009, the vertical coulter/rotary harrow + rotary hoe + cultivator with banded herbicide had the lowest breakeven price at \$0.135 kg^{-1} and the weedy check had the highest at \$0.223 kg^{-1}. In the resident area in both years, treatments with more reliance on mechanical implements had lower breakeven prices than in the subplot whereas the breakeven price of treatments relying on broadcast herbicides was more consistent between subplot and resident. In the resident area in 2008, the weedy check had the lowest breakeven soybean price at \$0.171 kg^{-1} and the vertical coulter/rotary harrow + herbicides the highest at \$0.255 kg^{-1}. In contrast to 2008, the weedy check had the lowest breakeven price in 2009 at \$0.123 kg^{-1} and the vertical coulter/rotary harrow + herbicides had the highest breakeven price at \$0.179 kg^{-1}.

Higher yields resulted in higher net returns in 2009 compared to 2008 (Tables 3.15 and 3.16). In the subplot at the lowest soybean price scenario of 0.330 kg^{-1}, the net returns ranged from -$35 to $427 ha^{-1} in 2008 , whereas at the highest soybean price scenario of 0.440 kg^{-1} net returns ranged from $92 to $722 ha^{-1} (Table 3.15). Regardless of the select price of soybean, the vertical coulter/rotary harrow produced the highest net returns whereas the weedy check and the vertical coulter/rotary harrow + rotary hoe treatments were the lowest. In the 2009 subplot at the lowest soybean price scenario of 0.330 kg^{-1} the net returns ranged from $171 to $705 ha^{-1}, whereas at the highest soybean price scenario of 0.440 kg^{-1} the net returns ranged from $345 to $1102 ha^{-1} (Table 3.16). The vertical coulter/rotary harrow + rotary hoe + cultivator with banded herbicides produced the highest net returns whereas the weedy check produced the lowest net return. Similar trends were seen in the resident area in both years, although treatments with more reliance on mechanical implements tended to have higher net returns in the resident area than in the subplot. For the entire range of soybean prices treatments including herbicides provided positive net returns in both 2008 and 2009, while treatments without herbicides were dependent on year and soybean prices.

Discussion

The mechanical implements did not affect soybean populations. Although the 2009 soybean population was within the expected range, the 2008 soybean population was lower than anticipated. The reduced population in 2008 was likely a result of cool, wet conditions, followed by a prolonged dry period following planting, leading to surface crusting and reduced emergence. The first rotary hoe operation was conducted while some plants were breaking through the surface crusting, but this operation did not affect soybean population. On farms relying on tillage, one purpose of the rotary hoe is to increase crop population by breaking the soil crust. However, previous research has also reported that the rotary hoe can reduce soybean population in conventional tillage systems (Buhler et al., 1992; Lovely et al., 1958). In no-till, the rotary hoe's ability to reduce the impact of soil crusting may be less effective than in tilled systems. The low uneven population in 2008 of this study may be more of a concern for weed management than yield. De Bruin and Pedersen (2008a) achieved 95% of the maximum yield in 76-cm rows with plant populations ranging from 157,300 to 211,800 plants ha^{-1}. However, in a situation with a low soybean population, weed growth may be favored. Arce et al. (2009) found higher soybean populations reduced weed biomass as a result of the higher populations increasing the competitiveness of the crop with weeds. None of the mechanical weed control tools in this study influenced soybean population.

The vertical coulter/rotary harrow and the cultivator's impact on surface residue raises concerns for soil erosion in this system. Our hypothesis that the combination of the vertical coulter/rotary harrow would provide weed control compared to a burndown herbicide, while maintaining residue levels of a no-till system is rejected. In addition to not provided the weed control of a burndown herbicide, the vertical coulter/rotary harrow reduced residue levels on average 21% compared to no-till. However, the vertical coulter/rotary harrow treatments remained above the 30% conservation level as defined by the Conservation Technology Information Center (CTIC, 2009). Also, our hypothesis that two to three passes of the rotary hoe would provide equivalent weed control to a soil-applied residual herbicide, while maintaining surface residue is partially rejected. The rotary hoe had no impact on surface residue, but only provided 41 to 52% weed control under high weed severity. In no till, with over 60% surface residue cover, Hooker et al. (1997) reported the rotary hoe was ineffective, which is consistent with previous research that indicated that the rotary hoe is less effective under conditions with greater than 30% residue cover (Cox et al., 1999; Springman, 1989). In our study, the rotary hoe was operated in between 30 to 50% surface residue, so if the residue amounts were less than 30% or perhaps differed in quality, the rotary hoe may have been a more effective weed control tool. The cultivator had the single greatest impact on residue cover and this finding partially rejects our hypothesis that the inter-row cultivator would provide between-row weed control comparable to soil-applied or post-emergence herbicides, while maintaining surface residue. However, the timing of cultivator operations relative to crop growth and soil conditions must be considered. Although full canopy cover was not reached until three to four weeks after cultivation, the developing crop canopy should help mitigate concerns over soil erosion potential with cultivation in soybean. Cultivation also increases surface roughness and helps break up crusted soil, potentially increasing water infiltration and reducing runoff potential (Alberts and Neibling, 1994). Because the cultivator does little soil inversion, lower levels of residue with this mechanical tool may be the result of reducing the residue size to smaller than the 2.4 mm diameter minimum required under the line transect method (Shelton et al., 1997) and/or redistribution of the residue on the surface from the inter-row into the crop row. Finally, corn stalks were shredded in the fall prior to spring management in this study and Shelton et al. (1995) reported that shredded stalks are more susceptible to losses caused by the mechanical implements used in this study. In order to maintain residue cover in combination with the mechanical weed control tools, spring stalk shredding or no stalk shredding could help maintain higher residue levels compared to the fall stalk shredding.

The results from this study demonstrate the ability to maintain weed control and yield, while incorporating certain mechanical tools and herbicide combinations. The vertical coulter/rotary harrow provided control of smaller weed seedlings (less than about 7 cm), but was ineffective on larger weeds (data not presented). In corn, the vertical coulter/rotary harrow provided similar weed control as a burndown herbicide (see Chapter 2). However, the corn was planted about a week earlier than soybean and the additional week allowed for weeds to outgrow the effective control size of the vertical coulter/rotary harrow in soybean. When relying on the vertical coulter/rotary harrow for pre plant weed control in later planted crops like soybean, monitoring weed emergence and weed size may be required which could result in additional operations (early and just prior to planting) for effective weed control. The mechanical only treatment results in this study disagree with previous research in conventional and conservation tillage systems that reported two rotary hoe and two cultivation passes produced weed control equal to soil-applied herbicides (Cox et al., 1999). In contrast, our results agree with previous results in no till from Hooker et al. (1997) that banded herbicides followed by cultivation can provide similar weed control and yield to broadcast herbicides. The findings of our research support our hypothesis that banded soil-applied herbicides at planting would provide improved weed control over the cultivator alone by provide in-row weed control, while the cultivator provided between-row weed control. The mechanical only treatments did not provide consistent weed control or maintain soybean yield, especially in 2008 when the effects from weed competition were more pronounced. While the frequency of cultivation was not tested in this study, the number of passes could influence weed control. Poston et al. (1992) reported that compared to one cultivation, a second cultivation reduced weed biomass an additional 70%. Our results found two cultivations alone were not as effective as a post-emergence herbicide. Weather and soil conditions and the size and composition of the weed seed bank play an important role in the effectiveness of cultivation. In systems relying on cultivation, monitoring weed control and emergence following the first cultivation maybe necessary to determine if a second operation is warranted.

Yield differences between treatments could have been impacted by row spacing. De Bruin and Pedersen (2008b) found soybean planted in 38-cm rows yielded 248 kg ha^{-1} more than 76-cm rows. Cox et al. (1999) compared 38 and 76-cm rows using cultivation only in the wide rows and reported a 7% yield increase in the 38 cm-row treatment associated with row spacing difference. Knezevic et al. (2003) reported that soybean planted in narrow row spacing increases soybean tolerance to weeds and may require less intensive weed management compared to wider rows. Other research showed that soybean canopy closure occurred 20 days later and weed biomass was greater in 76-cm rows than 19-cm rows (Hock et al., 2006). In our study, row spacing did not appear to influence soybean yield although the presence of Sclerotinia stem rot (*Sclerotinia sclerotiorum* Lib.) appeared to be more prevalent in 19-cm rows than 76-cm rows in 2009.

The incorporation of the mechanical implements in this study helped decrease herbicide use and has the potential for reducing herbicide pollution. However, mechanical implements alone did not effectively manage the weeds and some herbicide was necessary to help maintain soybean grain yield, particularly in 2008. In particular, the vertical coulter/rotary harrow plus rotary hoe did not adequately substitute for a burndown herbicide and soil-applied residual herbicides, so early season weed competition was likely a factor in these treatments. In contrast, banded soil-applied residual herbicides with cultivation provided effective weed control and maintained soybean yield, while at the same time reduced herbicide use by 60%. This reduction in herbicide could reduce runoff of metribuzin and metolachlor, the two soil-applied herbicides used in study, and the reduction may be attributed to the non-treated area acting as a natural filter helping to reduce herbicide losses (Gaynor and Wesenbeeck, 1995).

Herbicide-resistant weeds evolve with frequent herbicide use (Heap, 1997). Replacing vulnerable herbicides with effective mechanical controls such as the high residue cultivator could slow the development of herbicide-resistant weeds. In addition, post-emergence cultivation could be a used as a lower cost nonchemical alternative to an additional herbicide application for rescue control of resistant weed escapes. In this study, common ragweed, common lambsquarters, and horseweed, three weeds previously identified as herbicide-resistant in the region (Heap, 2010), were controlled with cultivation provided they were not directly in the soybean rows. However, cultivation can also result in the emergence of additional weeds and although late emerging weeds are less likely to compete with the crop, they can produce seeds, and potentially reduce crop quality and impact the harvest of some crops. Scouting the field following the first cultivation to determine if a second operation is warranted would help prevent successful late emerging weeds from going to seed.

Weed severity and management along with growing conditions (temperature and rainfall) helped determine grain yield which in turn influences the net returns. Reducing herbicide inputs decreases the cost of weed control, but yield must be maintained or net return is reduced. In addition, the herbicide program as well as equipment cost, size, and operating speeds will strongly influence cost comparisons between mechanical and chemical weed control. Cox et al. (1999) reported that weed management costs were higher with chemical weed control, but the higher yields increased net returns compared to alternative management programs. In addition, operation speed impacts the cost with slower operating speeds decreasing the area covered per hour and increasing the cost per hectare. In our study, the cultivator with the guidance system allowed for an increase in the operating speed by 4.9 kph. Paarlberg (1998) reported that increasing cultivator operating speed in no-till from 6.4 to 11.2 kph reduced costs and had a positive or neutral effect on weed control. However, a guidance system or skilled operator is required to reduce crop injury when increasing operating speed. Operator experience, field size, and field conditions would alter the speed of operation and the cost of the mechanical implements. This study was conducted with 4.6 meter wide or 6 row implements that is typical for the Mid-Atlantic region due to farm and field size. In the Midwestern US or regions where farm and field size are larger, implements could be wider. In addition, small field size reduces the efficiency of the operations due to turn around time. Larger fields would increase the land area that could be covered in an hour and decrease the cost per hectare of the implements.

The treatments without a post-emergence glyphosate application may be suitable in non-genetically modified (non-GMO) soybean and treatments relying solely on mechanical weed tools could be suitable for organic farmers. Banded herbicides followed by cultivation provided similar yields as the conventional no-till while providing similar breakeven prices and net returns. The premium paid for non-GMO soybean as well as the reduced cost of the seed could further support net returns provided the market for the product is available. Although both weed control and yield were reduced in the mechanical only treatments in 2008, the price premium paid for organic soybean grain would provide higher net returns than conventional production even if yields are slightly lower. Net returns using an organic premium were not calculated in this study, since inputs other than some weed control were conventional. Nutrient sources for organic systems include legumes, manures, compost and other natural fertilizer products and performance of the mechanical weed tools were not evaluated in these systems. Current research is examining the potential for high residue cultivation in organic systems relying on rolled cover crop mulches for early season weed suppression (Curran et al., 2009a; Curran et al., 2009b; Mirsky et al., 2009). Further research on the effectiveness of this mechanical tool in cover crops residues and organic systems is needed.

Conclusions

Overall, mechanical tillage implements alone did not provide adequate weed control, while integration with reduced herbicide inputs maintained acceptable levels of weed control, yields, and production cost. The vertical coulter/rotary harrow combination reduced residue cover and did not provide the weed control of a burndown herbicide. The high residue rotary hoe, while having no effect on residue, only provided 41 to 52% control under higher weed severity. Although the high residue cultivator reduced production costs relative to herbicide-based programs, it also reduced surface residue and when used alone did not provide weed control or soybean yields comparable to a program relying on post emergent herbicides. Banded herbicides followed by the cultivator provided weed control, yields, and net returns similar to a soil-applied residual broadcast and post emergent treatment. Combinations of herbicides and mechanical tools used under the proper weather and soil conditions have the potential to reduce herbicide use, while providing adequate weeds control, acceptable yield, and net returns.

Table 3.1. Description of experimental treatments investigated in soybean at Rock Springs in 2008 and 2009.

			Supplemental Herbicide†			
				Soil-Applied Residual		
Trt. No.	Row Width (cm)	Treatment	Pre-Plant Burndown	Broadcast	Banded	Post-Emergence
1	19	Conventional No-Till	X	X		X
2	19	VC/RH + Herbicides		X		X
3	19	VC/RH + Hoe + Post				X
4	76	Burndown + Hoe + Cultivator	X			
5	76	VC/RH + Hoe + Cultivator (Banded)			X	
6	76	VC/RH + Cultivator (Banded)			X	
7	76	VC/RH + Hoe + Cultivator				
8	76	VC/RH + Cultivator				
9	19	VC/RH + Hoe				
10	76	Weedy Check				

†Herbicide applications were made to treatments indicated by an "X".

Trt.No. = treatment number, VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe.

Table 3.2. Timing of operations and measurements for soybean in 2008 and 2009.

Operation	2008		2009	
	Date	DAP†	Date	DAP
Baseline Residue Count	8-Apr	-36	18-May	-3
Baseline Weed Count	8-Apr	-36	20-May	-1
1st VC/RH	9-Apr	-35	20-May	-1
Post VC/RH Residue Count	11-Apr	-33	—	—
Post VC/RH Weed Count	13-May	-2	—	—
2nd VC/RH	14-May	-1	—	—
Plant Soybean (& Band Treatments)	15-May	0	21-May	0
Burndown and Soil-Applied Herbicides	15-May	0	22-May	1
Post Planting Weed Count	21-May	7	1-June	11
Post Planting Residue Count	23-May	9	1-June	11
1st Rotary Hoe	26-May	12	1-June	11
2nd Rotary Hoe	9-June	26	10-June	18
3rd Rotary Hoe	19-June	36	—	—
Post Rotary Hoe Weed Count	25-June	42	24-June	34
Post Rotary Hoe Residue Count	26-June	43	25-June	35
Post Herbicide Treatment	1-July	48	26-June	36
1st Cultivation	1-July	48	28-June	38
2nd Cultivation	16-July	63	9-July	49
Post Cultivation Residue Count	17-July	64	14-July	54
Soybean Population Count	18-July	65	17-July	57
Post Cultivation Weed Count	25-July	72	14-July	54
Weed Biomass Collection	3-Sep	112	1-Sep	103
Soybean Harvest	22-Oct	161	6-Nov	169

†DAP= Days after Planting. Negative value indicates occurrence prior to planting

VC/RH = vertical coulter/rotary harrow.

Table 3.3. Description and price of tractors and implements investigated in soybean (2009 costs).

		Tractor Size (Kw)	Width / Capacity	Purchase Price ($)	Cost ha^{-1} ($ ha^{-1})	Operating Speed (kph)	Efficiency (%)
Tractor	Tractor 1	56	—	29,000†	—	—	—
	Tractor 2	78	—	71,000†	—	—	—
	Tractor 3	97	—	91,000†	—	—	—
Implement	Boom Sprayer	56	15.2 m	21,000†	7.22	8.1	65
	Vertical Coulter	78	4.3 m	22,582‡	20.66	11.3	70
	Rotary Harrow	78	4.6 m	15,000§	11.74	16.1	70
	Spinner Spreader	56	10.6 m^3	8,000¶	13.49	—	—
	No-till Planter	78	6 Rows / 4.6 m	25,000†	55.38	6.4	50
	No-till Planter w/Banding	78	6 Rows / 4.6 m	28,145#	58.71	6.4	50
	No-till Drill	97	4.6 m	33,000†	49.52	6.4	70
	Rotary Hoe	56	4.6 m	7,140†	7.14	16.1	70
	Hi-Res Cultivator	97	6 Rows / 4.6 m	23,000†	39.02	6.4	70
	Hi-Res Cultivator w/Guide	97	6 Rows / 4.6 m	28,000†	24.09	11.3	70
	Grain Cart	56	12.3 m^3	5,714¶	—	—	—
	Stalk Chopper	97	4.6 m	17,250†	36.42	8.1	70

† Price obtained from Lazarus (2009).

‡ Price obtained from Wil-Rich[25] for similar implement (personal communication, 2009).

§Price obtained from Phoenix Rotary Equipment for prototype implement (personal communication, 2009).

¶ Price obtained from Jayson Harper (personal communication, 2009).

Price of no-till planter plus cost of 757 liter sprayer and banding system.

Kw = Kilowatt, KPH = Kilometers per hour.

[25] Wil-Rich LLC, 17885 Highway 13 PO Box 1030, Wahpeton, ND 58075

Table 3.4. Cost of custom operations and inputs for soybean production (2009 input costs).

		Price ($)	Units
Custom Operations	Apply Lime	29.65†	hectare
	Combine Soybean	75.86†	hectare
	Soil Test	4.94‡	hectare
Inputs	Drilled Soybean Seed	168.13§	hectare
	Rowed Soybean Seed	146.78§	hectare
	Burndown herbicide	33.16¶	hectare
	Soil-applied broadcast herbicide	82.73¶	hectare
	Soil-applied banded herbicide	33.11¶	hectare
	Post-emergence herbicide	33.16¶	hectare
	Labor	12.50‡	hour
	Diesel	0.55§	liter

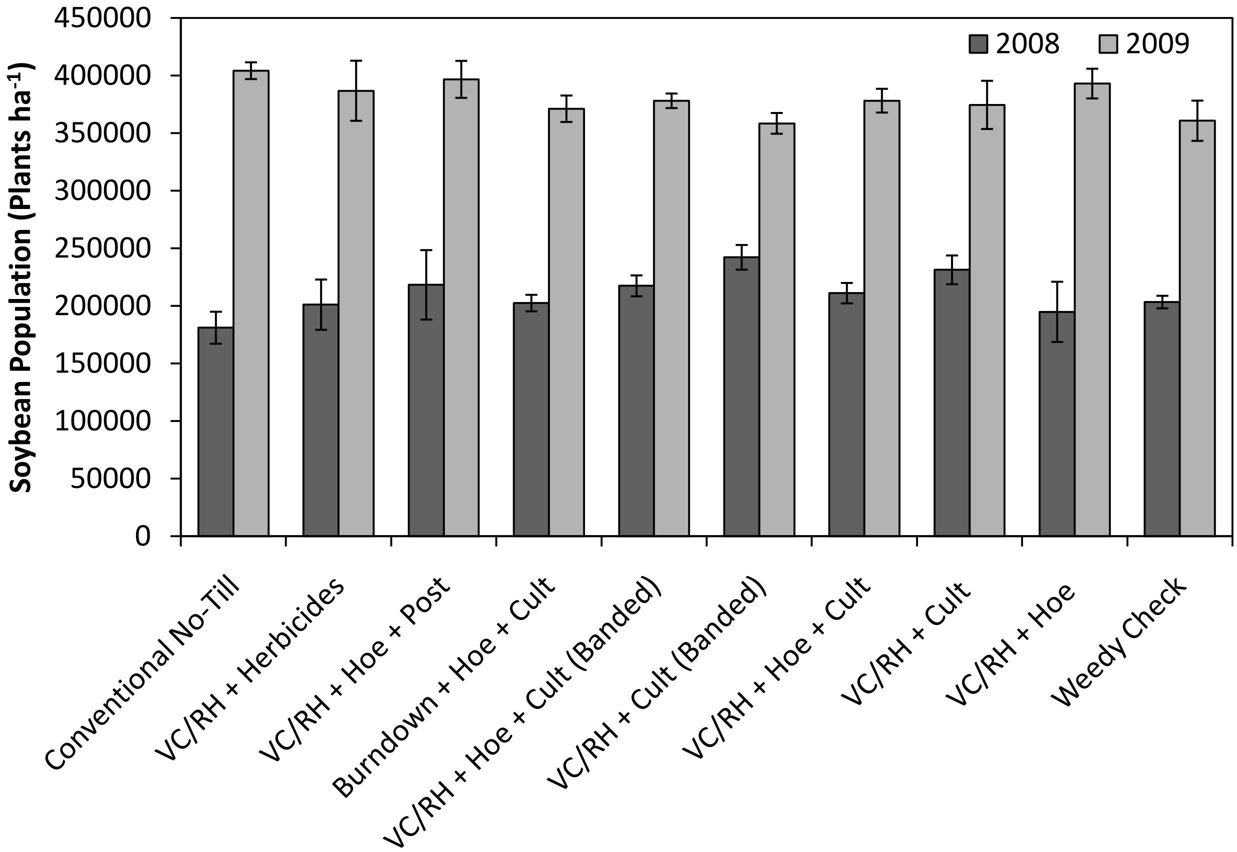
† Price obtained from Pike (2009).

‡ Price obtained from Jayson Harper (personal communication, 2009).

§ Price obtained from Penn State Agronomy Farm 2009 input prices (personal communication, 2009).

¶ Price obtained from William Curran (personal communication, 2009).

Figure 3.1. Mean soybean population following weed control operations in 2008 and 2009†.



†No significant difference between treatments in 2008 or 2009. Standard Error bars provided for each treatment mean. VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Table 3.5. Mean† surface residue levels following weed control operations for soybean in 2008 and 2009.

Treatment‡	2008				2009			
	8-Apr	23-May	26-Jun	17-Jul	18-May	1-Jun	25-Jun	14-Jul
	Residue (%)							
No-Till	84	65 a	59 a	45 a	47	40 a	37 a	31 a
VC/RH	—	49 b	42 b	31 b	—	33 b	31 ab	26 ab
Hoe	—	—	54 a		—	—	30 ab	—
VC/RH + Hoe	—	—	43 b	27 b	—	—	28 b	24 b
Hoe + Cult	—	—	—	15 c	—	—	—	21 bc
VC/RH + Cult	—	—	—	13 c	—	—	—	18 c
VC/RH + Hoe + Cult	—	—	—	11 c	—	—	—	17 c

† Similar letters in a column indicate no significant difference between treatments at $p<0.05$ (Tukey-Kramer mean separation test).

‡ Residue measurements from treatments that did not differ in at collection date were combined.

VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Figure 3.6. Mean† weed density by soybean treatment in 2008. Analyzed separately by dates, weed species, and subplot and resident areas.

Date	Treatment‡	Trt. No.	Subplot							Resident	
			AMARE	AMBEL	CHEAL	ERICA	SETFA	Other§	Total¶	Total	Percent of Subplot
			Weed Density (Plants m^{-2})								
8-Apr#	Baseline	1-10	0.0	0.0	0.0	0.0	0.0	0.0	0.0		—
13-May#	VC/RH	2,3,5-9	0.1 n.s.	3.8 n.s.	1.2 n.s.	0.0 n.s.	16.7 n.s.	6.8 a	28.9 a		—
	Weedy Check	1,4,10	0.1 n.s.	2.3 n.s.	0.9 n.s.	0.0 n.s.	9.9 n.s	2.3 b	15.5 b		—
21-May#	Conventional No-Till	1	0.0 n.s.	0.3 n.s.	0.5 n.s.	0.0 n.s.	0.6 n.s.	1.0 n.s.	2.4 n.s.		—
Post	VC/RH + Herbicides	2	0.0 n.s.	2.2 n.s.	0.5 n.s.	0.0 n.s.	1.3 n.s.	3.3 n.s.	6.5 n.s.		—
planting	Burndown	4	0.0 n.s.	0.3 n.s.	0.0 n.s.	0.0 n.s.	1.0 n.s.	0.2 n.s.	1.5 n.s.		—
	VC/RH (Banded)	5,6	0.0 n.s.	0.5 n.s.	0.1 n.s.	0.0 n.s.	0.9 n.s.	0.8 n.s.	2.3 n.s.		—
	VC/RH	3,7,8,9	0.0 n.s.	0.9 n.s.	0.1 n.s.	0.0 n.s.	1.2 n.s.	1.6 n.s.	3.8 n.s.		—
	Weedy Check	10	0.0 n.s.	3.0 n.s.	0.6 n.s.	0.0 n.s.	0.6 n.s.	6.0 n.s.	10.1 n.s.		—
25-Jun	Conventional No-Till	1	0.3 n.s.	0.7 b	0.0 c	0.0 b	6.0 c	0.0 e	7.0 e	0.0 d	0
Post hoe	VC/RH + Herbicides	2	0.0 n.s.	3.7 ab	0.0 c	0.0 b	9.7 c	0.7 de	14.0 e	0.8 cd	5
	Burndown + Hoe	4	6.3 n.s.	10.0 ab	3.3 bc	0.0 b	28.7 bc	3.3 bcd	51.7 cd	5.8 bc	11
	VC/RH + Hoe (Banded)	5	0.0 n.s.	4.3 ab	2.0 c	0.0 b	20.7 bc	2.3 cde	29.3 de	6.5 b	22
	VC/RH (Banded)	6	2.0 n.s.	7.0 ab	7.3 bc	0.3 b	39.7 bc	6.3 abc	62.7 bcd	13.8 ab	22
	VC/RH + Hoe	3,7,9	4.3 n.s.	6.3 ab	12.3 b	0.0 b	35.9 bc	5.6 bc	64.4 bc	17.7 ab	27
	VC/RH	8	3.7 n.s.	12.0 a	25.0 a	0.0 b	52.3 a	16.7 a	109.7 a	36.8 a	34
	Weedy Check	10	6.0 n.s.	10.7 a	10.3 bc	3.3 a	47.3 b	8.7 ab	86.3 ab	19.3 ab	22
25-Jul	Conventional No-Till	1	0.8 b	0.5 bc	1.5 cd	0.0 b	1.3 e	0.5 de	4.5 e	0.0 e	0
Post cult	VC/RH + Herbicides	2	0.8 b	1.0 b	0.0 d	0.0 b	5.5 de	1.5 cde	8.8 de	0.3 e	3
	VC/RH + Hoe + Post	3	0.5 b	3.8 ab	1.0 d	0.0 b	11.8 bcd	1.0 de	18.0 cd	3.8 cd	21
	Burndown + Hoe + Cult	4	19.3 a	3.0 ab	11.0 ab	0.0 b	11.3 bcd	10.5 ab	55.0 ab	8.8 bc	16
	VC/RH + Hoe + Cult (Banded)	5	0.0 b	1.3 b	0.5 d	0.0 b	7.5 cd	0.3 e	9.5 de	1.0 de	11
	VC/RH + Cult (Banded)	6	0.8 b	0.0 c	0.0 d	0.0 b	6.8 d	0.3 e	7.8 de	2.8 de	35
	VC/RH + Hoe + Cult	7	1.8 b	5.5 a	5.3 bc	0.3 b	14.3 bcd	5.0 abc	32.0 bc	18.0 ab	56
	VC/RH + Cult	8	2.0 b	6.8 a	9.0 abc	0.0 b	22.0 abc	3.5 bcd	43.3 bc	13.3 bc	31
	VC/RH + Hoe	9	17.5 a	10.0 a	24.0 a	0.0 b	52.0 a	13.0 a	116.5 a	31.8 a	27
	Weedy Check	10	3.5 b	13.8 a	11.0 ab	4.8 a	29.5 ab	10.0 ab	72.5 ab	31.8 a	44

† Similar letters at a date within a column indicate no significant difference between treatments at $p<0.05$ (Tukey-Kramer mean separation test). n.s. indicates no statistical difference between treatments.

‡ Weed density from treatments that did not differ in at collection date were combined.

§ Others include all other weeds observed.

¶Total equals the summation of the five weed species and others.

Weed density weed area was pooled due to no weed area*treatment interaction.

Trt. No. = Treatment Number, AMARE = redroot pigweed, AMBEL = common ragweed, CHEAL = common lambsquarters.

SETFA = giant foxtail, VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Figure 3.7. Mean† weed density by soybean treatment in 2009. Analyzed separately by dates, weed species, and subplot and resident areas.

Date	Treatment‡	Trt. No.	Subplot							Resident	
			AMARE	AMBEL	CHEAL	ERICA	SETFA	Other§	Total¶	Total	Percent of Subplot
			Weed Density (Plants m^{-2})								
20-May#	Baseline	1-10	0.0	7.2	3.7	1.2	27.8	9.3	49.1		
1-Jun#	Conventional No-Till	1	0.1 n.s.	0.3 b	0.0 b	0.0 b	0.8 n.s.	0.8 c	1.6 c		—
Post planting	VC/RH + Herbicides	2	0.6 n.s.	3.6 ab	1.6 ab	0.6 b	6.9 n.s.	6.5 ab	20.1 b		—
	Burndown	4	0.0 n.s.	0.4 b	0.1 b	0.0 b	2.6 n.s.	0.3 c	4.8 c		—
	VC/RH (Banded)	5,6	0.4 n.s.	1.5 ab	1.1 ab	0.0 b	8.4 n.s.	3.3 bc	16.3 b		—
	VC/RH	3,7,8,9	1.3 n.s.	1.0 b	1.2 ab	0.1 b	7.1 n.s.	3.4 bc	15.6 b		—
	Weedy Check	10	0.6 n.s.	9.9 a	4.3 a	2.0 a	22.1 n.s.	15.5 a	61.0 a		—
24-Jun	Conventional No-Till	1	0.0 b	0.5 c	0.0 c	0.0 b	3.3 d	0.5 c	4.3 f	0.3 e	6
Post hoe	VC/RH + Herbicides	2	2.8 b	2.3 bc	4.3 bc	1.0 b	3.3 d	6.8 abc	20.3 ef	11.0 abc	54
	Burndown + Hoe	4	10.3 ab	4.8 bc	14.5 bc	1.5 b	54.0 b	6.5 abc	91.5 bc	5.3 cd	6
	VC/RH + Hoe (Banded)	5	0.5 b	2.3 bc	1.8 bc	0.0 b	17.5 cd	1.8 c	23.8 def	3.8 d	16
	VC/RH (Banded)	6	1.5 b	3.3 bc	4.3 bc	1.0 b	45.5 bc	6.3 abc	61.8 cde	8.0 bcd	13
	VC/RH + Hoe	3,7,9	10.0 b	6.3 b	20.6 b	0.6 b	41.3 bc	6.2 bc	84.9 cd	14.8 ab	17
	VC/RH	8	24.0 a	6.0 bc	49.5 a	3.0 b	84.3 a	10.5 ab	177.3 a	31.8 a	18
	Weedy Check	10	7.0 b	20.0 a	12.8 bc	12.8 a	63.8 ab	13.8 a	130.0 ab	22.3 ab	17
14-Jul	Conventional No-Till	1	0.0 c	0.0 e	0.0 e	0.0 b	2.3 cd	0.0 f	2.3 f	0.5 e	22
Post cult	VC/RH + Herbicides	2	1.3 bc	0.5 de	2.5 cde	0.0 b	2.8 d	2.0 c-f	9.0 ef	3.0 de	33
	VC/RH + Hoe + Post	3	1.0 bc	0.5 de	1.8 cde	0.0 b	8.0 cd	3.3 cde	14.5 cde	1.3 e	9
	Burndown + Hoe + Cult	4	4.5 ab	4.5 bc	3.8 cde	1.3 b	16.8 a-d	8.3 abc	39.0 bc	6.3 cde	16
	VC/RH + Hoe + Cult (Banded)	5	0.0 c	2.3 cde	1.0 de	0.3 b	6.8 cd	2.0 def	12.3 def	3.0 de	24
	VC/RH + Cult (Banded)	6	0.0 c	0.3 de	0.5 de	0.0 b	7.0 cd	0.8 ef	8.5 def	0.8 e	9
	VC/RH + Hoe + Cult	7	2.8 bc	5.5 bc	7.5 bcd	0.5 b	12.3 bcd	6.8 b-e	34.3 cd	8.8 bcd	26
	VC/RH + Cult	8	5.0 ab	2.8 bcd	13.8 abc	0.5 b	17.8 abc	6.5 a-d	46.3 bc	17.5 abc	38
	VC/RH + Hoe	9	17.0 a	9.0 ab	35.5 a	1.5 b	58.8 ab	18.3 ab	138.5 ab	35.3 ab	25
	Weedy Check	10	3.5 bc	19.0 a	21.0 ab	22.8 a	79.8 a	26.3 a	171.3 a	43.3 a	25

† Similar letters at a date within a column indicate no significant difference between treatments at $p<0.05$ (Tukey-Kramer mean separation test). n.s. indicates no statistical difference between treatments.

‡ Weed density from treatments that did not differ in at collection date were combined.

§ Others include all other weeds observed.

¶Total equals the summation of the five weed species and others.

Weed density weed area was pooled due to no weed area*treatment interaction.

Trt. No. = Treatment Number, AMARE = redroot pigweed, AMBEL = common ragweed, CHEAL = common lambsquarters.

ERICA = Horseweed, SETFA = giant foxtail, VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Table 3.8. ANOVA output for the effect of weed biomass on soybean treatment, weed area, year, and interactions.

Effect	Num DF	Den DF	F Value	Pr > F
Year	1	90	1.89	0.1727
Treatment	9	27	27.55	<.0001
Weed Area	1	90	89.79	<.0001
Weed Area*Treatment	9	90	4.64	<.0001
Year*Treatment	9	90	8.11	<.0001
Year*Weed Area*Treatment	9	90	3.39	0.0013
Year*Weed Area	1	90	17.42	<.0001
2008				
Treatment	9	27	11.49	<.0001
Weed Area	1	30	69.60	<.0001
Treatment* Weed Area	9	30	4.46	0.0009
Subplot	9	27	22.71	<.0001
Resident	9	27	8.00	<.0001
2009				
Treatment	9	27	11.52	<.0001
Weed Area	1	30	5.41	0.0269
Treatment*Weed Area	9	30	0.44	0.9031

Table 3.9. Mean† weed biomass by soybean treatment in 2008.

Treatment	Subplot AMARE		AMBEL		CHEAL		ERICA		SETFA		Other‡		Total§		Resident Total		Percent of Subplot
	Weed Biomass (kg ha^{-1})																
Conventional No-Till	0	n.s.	11	b	0	c	0	b	70	bc	1	b	82	d	7	d	9
VC/RH + Herbicides	71	n.s.	64	b	36	bc	0	b	208	ab	3	ab	382	cd	9	d	2
VC/RH + Hoe + Post	35	n.s.	61	b	399	abc	0	b	16	c	210	a	721	cd	95	d	13
Burndown + Hoe + Cult	160	n.s.	1158	a	67	ab	102	ab	1079	a	25	ab	2591	abcd	243	bcd	9
VC/RH + Hoe + Cult (Banded)	21	n.s.	283	ab	17	bc	0	b	474	ab	4	ab	799	bcd	68	d	9
VC/RH + Cult (Banded)	0	n.s.	151	ab	6	bc	0	b	406	ab	0	b	563	cd	149	cd	26
VC/RH + Hoe + Cult	212	n.s.	1468	a	1711	a	43	b	742	a	30	ab	4206	a	827	b	20
VC/RH + Cult	87	n.s.	1801	a	204	a	50	b	866	a	13	ab	3021	abc	760	bc	25
VC/RH + Hoe	118	n.s.	1645	a	492	a	0	b	1252	a	18	ab	3524	ab	1615	a	46
Weedy Check	178	n.s.	1784	a	518	a	398	a	1200	a	39	ab	4117	a	1738	a	42

† Similar letters in a column indicate no significant difference between treatments at $p<0.05$ (Tukey-Kramer mean separation test).

‡ Others include all other weeds observed.

§Total equals the summation of the five weed species and others.

AMARE = redroot pigweed, AMBEL = common ragweed, CHEAL = common lambsquarters, SETFA = giant foxtail.

VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Table 3.10. Mean† weed biomass by soybean treatment in 2009

Treatment‡	AMARE		AMBEL		CHEAL		ERICA		SETFA		Other§		Total¶	
	Weed Biomass (kg ha^{-1})													
Conventional No-Till	0	c	0	n.s.	0	d	0	b	9	n.s.	1	d	10	e
VC/RH + Herbicides	0	bc	0	n.s.	0	d	0	b	1	n.s.	0	d	2	e
VC/RH + Hoe + Post	0	bc	0	n.s.	1	d	3	b	12	n.s.	1	d	17	e
Burndown + Hoe + Cult	78	ab	397	n.s.	120	abc	153	b	406	n.s.	69	ab	1223	bcd
VC/RH + Hoe + Cult (Banded)	0	bc	221	n.s.	224	cd	0	b	153	n.s.	117	ab	714	d
VC/RH + Cult (Banded)	109	abc	44	n.s.	380	bcd	0	b	184	n.s.	9	cd	724	cd
VC/RH + Hoe + Cult	143	ab	735	n.s.	254	abc	478	ab	206	n.s.	86	bc	1902	bcd
VC/RH + Cult	190	a	350	n.s.	482	ab	152	b	347	n.s.	126	ab	1647	bc
VC/RH + Hoe	105	a	1216	n.s.	671	a	1153	ab	244	n.s.	169	ab	3558	ab
Weedy Check	49	abc	1329	n.s.	798	a	4549	a	171	n.s.	616	a	7512	a

† Similar letters in a column indicate no significant difference between treatments at $p<0.05$ (Tukey-Kramer mean separation test).

‡ Weed density weed area was pooled due to no weed area*treatment interaction

§ Others include all other weeds observed.

¶Total equals the summation of the five weed species and others.

AMARE = redroot pigweed, AMBEL = common ragweed, CHEAL = common lambsquarters, ERICA = horseweed, SETFA = giant foxtail.

VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Table 3.11. ANOVA output for the effect of soybean yield on treatment, weed area, year, and interactions.

Effect	Num DF	Den DF	F Value	Pr > F
Year	1	90	480.85	<.0001
Treatment	9	27	13.84	<.0001
Weed Area	1	90	48.42	<.0001
Weed Area*Treatment	9	90	8.21	<.0001
Year*Treatment	9	90	5.26	<.0001
Year*Weed Area*Treatment	9	90	2.23	0.0268
Year*Weed Area	1	90	3.15	0.0795
2008				
Treatment	9	27	29.24	<.0001
Weed Area	1	30	113.78	<.0001
Treatment*Weed Area	9	30	16.98	<.0001
Subplot	9	27	30.89	<.0001
Resident	9	27	10.09	<.0001
2009				
Treatment	9	27	6.75	<.0001
Area	1	30	19.24	0.0001
Treatment*Weed Area	9	30	6.80	<.0001
Subplot	9	27	8.57	<.0001
Resident	9	27	3.72	0.0038

Table 3.12. Mean† soybean yield by treatment in 2008 and 2009.

Treatment	2008				2009			
	Subplot		Resident		Subplot		Resident	
	Grain Yield (kg ha^{-1})							
Conventional No-Till	2597	a	2661	a	3221	a	3034	abc
VC/RH + Herbicides	2279	ab	2236	bcd	2982	ab	3000	abc
VC/RH + Hoe + Post	2676	a	2390	ab	3362	a	3557	ab
Burndown + Hoe + Cult	1515	cd	2501	abc	3112	ab	3059	abc
VC/RH + Hoe + Cult (Banded)	2011	bc	2233	bcd	3603	a	3625	a
VC/RH + Cult (Banded)	2464	ab	2345	abc	3287	a	3204	abc
VC/RH + Hoe + Cult	1427	d	2146	cd	3072	ab	3374	abc
VC/RH + Cult	1454	d	2078	cd	2887	ab	3077	abc
VC/RH + Hoe	1151	d	1893	d	2141	bc	2781	c
Weedy Check	1055	d	2059	cd	1584	c	2863	bc

†Similar letters in a column indicate no significant difference between treatments at $p<0.05$

(Tukey-Kramer mean separation test).

VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Table 3.13. Weed control cost, total production cost, and breakeven price by soybean treatment in 2008.

Treatment	Weed Control Cost ($ ha^{-1})				Total Production Costs† ($ ha^{-1})	Breakeven Price ($ kg^{-1})	
	Herbicide	Machinery	Labor	Total		Subplot	Resident
Conventional No-Till	149.05	11.32	3.11	163.48	537.70	0.207	0.202
VC/RH + Herbicides	115.89	63.75	15.37	195.02	569.33	0.250	0.255
VC/RH + Hoe + Post	33.16	72.25	21.08	126.49	498.24	0.186	0.209
Burndown + Hoe + Cult	33.16	61.08	15.74	109.99	465.37	0.307	0.186
VC/RH + Hoe + Cult (Banded)	33.11	111.20	26.44	170.75	527.27	0.262	0.236
VC/RH + Cult (Banded)	33.11	97.04	19.18	149.33	505.38	0.205	0.215
VC/RH + Hoe + Cult	0.00	107.86	26.44	134.30	489.64	0.343	0.228
VC/RH + Cult	0.00	93.70	19.18	112.88	467.75	0.322	0.225
VC/RH + Hoe	0.00	66.59	19.52	86.12	459.79	0.399	0.243
Weedy Check	0.00	0.00	0.00	0.00	353.06	0.335	0.171

† Includes all production costs except for land and management charges.

VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Table 3.14. Weed control cost, total production cost, and breakeven price by soybean treatment in 2009.

Treatment	Weed Control Cost ($ ha^{-1})				Total Production Cost† ($ ha^{-1})	Breakeven Price ($ kg^{-1})	
	Herbicide	Machinery	Labor	Total		Subplot	Resident
Conventional No-Till	149.05	11.32	3.11	163.48	537.28	0.167	0.177
VC/RH + Herbicides	115.89	37.54	9.24	162.67	535.90	0.180	0.179
VC/RH + Hoe + Post	33.16	41.32	12.53	87.01	457.49	0.147	0.150
Burndown + Hoe + Cult	33.16	56.36	13.32	102.85	457.49	0.136	0.129
VC/RH + Hoe + Cult (Banded)	33.11	80.26	17.89	131.26	486.38	0.135	0.134
VC/RH + Cult (Banded)	33.11	70.82	13.05	116.98	471.80	0.144	0.147
VC/RH + Hoe + Cult	0.00	76.92	17.89	94.81	448.74	0.146	0.133
VC/RH + Cult	0.00	67.48	13.05	80.53	434.16	0.150	0.141
VC/RH + Hoe	0.00	35.66	10.97	46.63	416.03	0.194	0.150
Weedy Check	0.00	0.00	0.00	0.00	353.06	0.223	0.123

† Includes all production costs except for land and management charges.

VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Table 3.15. Net returns† by treatment at select soybean prices in 2008.

	Price of Soybean ($ kg^{-1})							
	0.330		0.367		0.403		0.440	
Treatment	Subplot	Resident	Subplot	Resident	Subplot	Resident	Subplot	Resident
	Returns above total cost ($ ha^{-1})							
Conventional No-Till	321	343	417	440	512	538	608	636
VC/RH + Herbicides	218	204	301	286	385	368	469	450
VC/RH + Hoe + Post	427	333	526	421	624	508	722	596
Burndown + Hoe + Cult	43	369	99	461	155	553	210	645
VC/RH + Hoe + Cult (Banded)	179	252	253	334	327	416	400	498
VC/RH + Cult (Banded)	343	304	434	390	524	476	615	562
VC/RH + Hoe + Cult	23	261	76	340	128	419	181	497
VC/RH + Cult	47	253	100	329	154	406	207	482
VC/RH + Hoe	-35	210	7	280	49	349	92	419
Weedy Check	-4	328	35	404	73	479	112	555

† Includes all production costs except for land and management charges.

VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

Table 3.16. Net returns† by treatment at select soybean prices in 2009.

Treatment	Price of Soybean ($ kg^{-1}) 0.330 Subplot	0.330 Resident	0.367 Subplot	0.367 Resident	0.403 Subplot	0.403 Resident	0.440 Subplot	0.440 Resident
	Returns above total cost ($ ha^{-1})							
Conventional No-Till	528	466	646	578	765	689	883	801
VC/RH + Herbicides	450	456	560	566	670	677	779	787
VC/RH + Hoe + Post	572	554	686	666	800	779	915	891
Burndown + Hoe + Cult	654	719	778	849	901	980	1025	1111
VC/RH + Hoe + Cult (Banded)	705	712	837	846	970	979	1102	1112
VC/RH + Cult (Banded)	615	588	736	705	857	823	977	941
VC/RH + Hoe + Cult	567	667	680	791	793	915	906	1039
VC/RH + Cult	520	584	627	697	733	810	839	923
VC/RH + Hoe	292	503	371	606	449	708	528	810
Weedy Check	171	594	229	699	287	804	345	909

† Includes all production costs except for land and management charges.

VC/RH = vertical coulter/rotary harrow, Hoe = rotary hoe, Cult = cultivator.

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Chapter 4

Conclusions

The challenge presented in this project was to create an integrated weed management system that was less reliant on herbicides prone to off-site movement and/or resistance development while maintaining surface residue that is important for soil conservation. The objective for this research was to evaluate mechanical implements for weed control in high residue corn and soybean. For the most part, similar results were seen in both the corn and soybean studies and similar trends were observed between the supplemental and existing weed populations. The vertical coulter/rotary harrow provided control of smaller weed seedlings (less than about 7 cm), but was ineffective on larger weeds and reduced residue by 15-21%. The vertical coulter/rotary harrow provided similar levels of weed control as a burndown herbicide in corn, but not in soybean. Because corn was planted about a week earlier than soybean and the additional week allowed weeds to outgrow the effective control size of the vertical coulter/rotary harrow in soybean. The rotary hoe, while having minimum effect on residue, provided inconsistent results. The high residue cultivator reduced surface residue below 30% cover and when used alone did not provide weed control or yields comparable to a program relying on post-emergence herbicides. Banded herbicides followed by the cultivator provided weed control, yields, and net returns similar to a soil-applied residual broadcast and post-emergence treatment. Combinations of herbicides and mechanical tools under the proper weather and soil conditions have the potential to reduce herbicide use, while providing acceptable weeds control, crop yield, and net returns.

Although the treatment combinations tested in this study greatly increased our understanding of the effectiveness of the individual mechanical implements, there were treatments that maybe could have been excluded, as well as treatments that should have been included in the study. The combination of banded herbicides and rotary hoe (vertical coulter/rotary harrow + rotary hoe + cultivator with banded herbicide treatment) did not increase weed control or improve yields over banded herbicides alone, and therefore only increased weed control cost. Because the rotary hoe and banded herbicides are both early season weed control options, to follow banded herbicides with the rotary hoe, which would only need to provide between-row weed control, may be a hard sell for adoption. In hindsight, the rotary hoe with banded herbicides may be redundant and unrealistic from a farmer's perspective. In addition, the vertical coulter/rotary harrow + rotary hoe treatment was used to examine narrow row soybean without herbicides, but proved to be have similar weed biomass and yield as the weedy check. These treatments could have been excluded and additional treatments could have further explored the value of banded herbicides. Banded soil-applied herbicides followed by cultivation appears to be a practical post planting weed control strategy that uses mechanical implements and reduced herbicide inputs. While in this research banded herbicides were only used on treatments following the vertical coulter/rotary harrow, a burndown herbicide with banded herbicides followed by cultivation could be an alternative that would have a higher degree of acceptance. Although a well-timed vertical coulter/rotary harrow operation was as effective as a burndown herbicide, the adoption may be limited especially in the absence of early emerging herbicide-resistant weeds (e.g. horseweed), because of time constraints during the planting season.

Future research should further investigate these mechanical implements as well as other implements for weed control in high residue corn and soybean systems. This research should include the investigation of other conservation tillage implements (e.g. Case IH[1] True Tandem 330 Turbo, Phoenix[2] Till-Lite, and Great Plains[3] Turbo Chopper and Ultra-Till) for their potential pre-plant weed control that may be more effective and/or maintain more residue. For example, these implements may control the larger weeds that escaped the vertical coulter/rotary harrow. Additionally, future research should investigate the rotary hoe under different residue types, quantities, and timings to better identify where this tool might fit in conservation tillage systems. If residue cover is the limiting factor in the effectiveness of the rotary hoe, conducting research following soybean or corn for silage could identify a potential fit for the rotary hoe in conservation tillage systems. In addition, future programs should investigate the cultivator for weed control while performing additional services such as side dressing nitrogen in corn. Also, a decision tool based on weather and weed density to determine the optimum number of cultivations required for adequate weed control in conservation tillage systems could be valuable. Additional services could reduce cost and increase acceptance of mechanical implements in high residue systems. On-farm research will be instrumental for adoption and bring to light other concerns farmers may have with the mechanical tools. Furthermore, research is needed to determine the benefit of integrated mechanical weed management in high residue systems on herbicide resistance weeds and water quality. For example, new models comparing the evolution of herbicide-resistant weeds

[1] Case IH, 700 State Street, Racine, WI 53404
[2] Phoenix Rotary Equipment, 33908 128th Street County Road 4, Waseca, MN 56093
[3] Great Plains Mfg Inc., 1525 E. North Street, Salina, Kansas 67401

when including mechanical implements in high residue systems to no-till as well as runoff and leaching studies of these systems could be valuable to further support the use of these implements. Finally, additional research should investigate soil related concerns of mechanical weed control tools in high residue systems for a more complete understanding of the soil erosion potential with these implements along with the impact on soil organisms, changes in carbon sequestration, and effects on soil structure. This type of information will be necessary when discussing any type of tillage with strongly committed no-till farmers.

Additional research would provide a better understanding of the implements abilities and potentially increase the acceptance of mechanical weed control implements in high residue systems, in particular the cultivator. Adoption of the cultivator in high residue corn and soybean systems could potentially delay the development of herbicide-resistant weeds and reduce soil erosion and other environmental issues. The results from this study as well as further research could not only result in increased adoption of mechanical implements such as the cultivator for weed control in high residue systems, but also provide the necessary information for government policies and incentives along with other agencies to promote integrated weed management in high residue corn and soybean systems.