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Overcoming Weed Management Challenges in Cover Crop–Based Organic Rotational No-Till Soybean Production in the Eastern United States

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Cover crop–based organic rotational no-till soybean production has attracted attention from farmers, researchers, and other agricultural professionals because of the ability of this new system to enhance soil conservation, reduce labor requirements, and decrease diesel fuel use compared to traditional organic production. This system is based on the use of cereal rye cover crops that are mechanically terminated with a roller-crimper to create in situ mulch that suppresses weeds and promotes soybean growth. In this paper, we report experiments that were conducted over the past decade in the eastern region of the United States on cover crop–based organic rotational no-till soybean production, and we outline current management strategies and future research needs. Our research has focused on maximizing cereal rye spring ground cover and biomass because of the crucial role this cover crop plays in weed suppression. Soil fertility and cereal rye sowing and termination timing affect biomass production, and these factors can be manipulated to achieve levels greater than 8,000 kg ha^{-1}, a threshold identified for consistent suppression of annual weeds. Manipulating cereal rye seeding rate and seeding method also influences ground cover and weed suppression. In general, weed suppression is species-specific, with early emerging summer annual weeds (e.g., common ragweed), high weed seed bank densities (e.g. $>$ 10,000 seeds m^{-2}), and perennial weeds (e.g., yellow nutsedge) posing the greatest challenges. Due to the challenges with maximizing cereal rye weed suppression potential, we have also found high-residue cultivation to significantly improve weed control. In addition to cover crop and weed management, we have made progress with planting equipment and planting density for establishing soybean into a thick cover crop residue. Our current and future research will focus on integrated multitactic weed management, cultivar selection, insect pest suppression, and nitrogen management as part of a systems approach to advancing this new production system.

Nomenclature: Common ragweed, *Ambrosia artemisiifolia* L.; yellow nutsedge, *Cyperus esculentus* L.; cereal rye, *Secale cereale* L.; corn, *Zea mays* L.; soybean, *Glycine max* (L). Merr.; wheat, *Triticum aestivum* L.

Key words: Reduced-tillage, organic.

La producción orgánica de soya en sistemas de rotación con cero labranza basados en cultivos de cobertura, ha atraído la atención de productores, investigadores y otros profesionales agrícolas por la habilidad de este nuevo sistema de mejorar la conservación del suelo, reducir los requerimientos de mano de obra y disminuir el uso de combustible diesel en comparación con la producción orgánica tradicional. Este sistema está basado en el uso de centeno como cultivo de cobertura el cual es terminado mecánicamente con un rodillo de cuchillas para crear una cobertura de residuos in situ que suprime malezas y promueve el crecimiento de la soya. En este artículo, reportamos experimentos que fueron realizados durante la década pasada en la región este de los Estados Unidos sobre la producción orgánica de soya en sistemas de rotación con cero labranza basados en cultivos de cobertura, y delineamos las estrategias actuales de manejo y las necesidades futuras de investigación. Nuestra investigación se ha enfocado en maximizar la cobertura y la biomasa del centeno de primavera debido al papel crucial que este cultivo de cobertura juega en la supresión de malezas. La fertilidad del suelo y el momento de siembra y término del centeno afectan la producción de biomasa, y estos factores pueden ser manipulados para alcanzar niveles mayores a 8,000 kg ha^{-1}, el cual es el umbral identificado para la supresión consistente de malezas anuales. Manipular la densidad y métodos de siembra también influencia la cobertura del suelo y la supresión de malezas. En general, la supresión de malezas es específica a la especie, siendo las malezas anuales de verano que emergen temprano (e.g. *Ambrosia artemisiifolia*), los banco de semillas con altas densidades (e.g. $>$10,000 semillas m^{-2}), y las malezas perennes (e.g. *Cyperus esculentus*) los mayores retos. Debido a los retos de maximizar el potencial de supresión de malezas del centeno, hemos encontrado que el cultivar con altos residuos también puede mejorar el control de malezas significativamente. Adicionalmente al cultivo de cobertura y el manejo de malezas, hemos progresado con el equipo y la densidad de siembra para el establecimiento de la soya en capas gruesas de residuos de cultivos de cobertura. Nuestra investigación actual y futura se centrará en el manejo integrado de malezas multitáctico, la selección de cultivares, la supresión de plagas insectiles, y el manejo del nitrógeno como parte de un enfoque de sistemas para el avance de este nuevo sistema de producción.

Soil and water conservation is essential to the long-term sustainability of crop production systems. Over the past 20 yr, no-tillage management has dramatically increased the ability to conserve soil resources (Franzluebbers 2002, 2005; Pesant et al. 1987; Spargo et al. 2008), while simultaneously reducing labor and production costs (Parsch et al. 2001). However, overreliance on herbicides has led to the selection of herbicide-resistant weeds, which has in some cases more than doubled weed management expenses (Price et al. 2011). As a

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result, soil conservation using no-till practices has constrained long-term weed management efficacy and sustainability in conventional agriculture. In contrast, traditional organic grain production requires extensive tillage that integrates diverse physical and cultural tactics, reducing the opportunity for weeds to develop resistance to a given tactic. Weed management in organic grain crop production typically involves full-inversion moldboard plow or disc tillage, cultivation with a tine weeder or rotary hoe, and interrow cultivation. On the other hand, organic cropping systems typically use cover crops, return crop residues, and use C-rich fertility amendments and crop diversification, which offset the negative impacts of tillage (Teasdale et al. 2007). An increasing number of growers are interested in developing reduced-tillage systems that integrate the soil-conserving and labor-saving features of conventional no-tillage systems with the soil building practices used in organic production. In this summary of our recent research, we describe advancements in the development of a cover crop–based, organic rotational no-till soybean production system that balances the trade-offs between soil conservation and weed management.

We first introduce our region and discuss the critical role of cover crops in this system and how they must be manipulated to maximize weed suppression. We then discuss the necessary equipment for optimizing soybean establishment and multi-tactic weed management with an emphasis on high-residue cultivation. We conclude with a broader discussion on the integration of this soybean production system into existing organic grain rotations.

Cover Crop–Based Organic Rotational No-Till System: Production and Ecosystem Services

In response to a rising interest for reducing tillage in organic crop production, growers and researchers have developed an organic crop and soil management system that has since been termed *cover crop–based organic rotational no-till* (Mirsky et al. 2012). This approach relies on mature cover crop residue to be used as mulch in place of standard weed management tactics such as herbicides and cultivation. In the cover crop–based organic rotational no-till system, winter annual cover crops are controlled in the spring using a roller-crimper, which provides in situ surface mulch that physically suppresses weeds. The cash crop is then no-till planted into the cover crop mulch. However, tillage is typically used prior to seeding the cover crop to optimize establishment and to control perennial weeds; thus it is a rotational tillage system.

Cereal rye has been the primary cover crop used in conjunction with soybean (Berstein et al. 2011; Davis 2010; Delate et al. 2012; Moore et al. 1994). This cover crop has been found to be the most reliable winter annual cover crop for providing a wide range of ecological services in the eastern region (Shipley et al. 1992). Cereal rye is one of the earliest flowering species, extremely cold tolerant, produces the most biomass, and has rapid emergence (Clark 2007). Furthermore, cereal rye has been coupled with soybean for its residue persistence and flexible establishment date (Mirsky et al. 2011; Ruffo and Bollero 2003).

The perceived inability to use no-till for organic crop production has been suggested as a key factor limiting the adoption of organic practices by conventional producers (Cavigelli et al., 2013). Labor required for organic grain production is another major constraint limiting the amount of organically managed cropland. Effective strategies for reducing tillage in organic systems could serve to attract more farmers to adopt organic production and reduce current organic feed grain shortages. Integrating no-till practices can potentially improve the sustainability of organic grain production by reducing diesel fuel use and labor requirements. In a recent analysis of energy use in a 3-yr organic corn–soybean–wheat rotation, cover crop–based rotational no-till required 27% less diesel fuel and 31% less labor than traditional organic management (Mirsky et al. 2012; Ryan 2010). This reduction in diesel fuel use and labor is largely a result of eliminating seedbed preparations (tillage, disking, and cultipacking) and common cultivation approaches (rotary hoe or tine-weeders at crop establishment followed by interrow cultivators) used for weed control in traditional tillage-based organic corn and soybean production.

Winter annual cover crops provide numerous ecosystem services that improve crop performance, nutrient cycling, and overall cropping system function (Snapp et al. 2005). Cover crops protect surface- and groundwater quality by decreasing soil erosion, nitrogen (N) leaching, and phosphorus (P) runoff (Adeli et al. 2011; Qi and Helmers 2009). Using cover crops to improve N retention through scavenging and biological N fixation can lower fertilizer costs (Dabney et al. 2010. Increased N conservation, addition, or both with cover crops reduces the reliance of organic cropping systems on animal manure thereby reducing excessive P loading. Cover crops can also provide habitat for pollinators (Decourtye et al. 2010) and other beneficial insects, such as weed seed predators (Ward et al. 2011). Furthermore, the cover crop–based organic rotational no-till system relies on terminating cover crops at anthesis, which can result in one to two orders of magnitude greater root and shoot biomass relative to cover crops grown in traditional organic or conventional cropping systems. Despite these benefits, cover crop performance is of utmost importance because of the critical role cover crops play in weed suppression. It is also important to note that the services provided by cover crops are completely transferable to conventional systems, but their value may be reduced given the broader range of selective pest and precision fertility management options that are available to conventional growers.

Corn and soybean are the primary commodity crops that have been evaluated in the cover crop–based organic rotational no-till system in the central and eastern United States. While both crops can produce competitive yields in this system, the performance of corn has been more variable than soybean (Delate et al. 2012; Mirsky et al. 2012; Reberg-Horton et al. 2012). Greater success with soybean has been attributed to several factors. First, both crops are vulnerable to reduced plant populations due to poor seed placement and seed and seedling feeding herbivores; however, soybean has greater plasticity than corn and can more effectively compensate for stand losses. Second, soybean is a legume and does not have the same nitrogen management (i.e., source, timing, and placement) constraints as corn. Third, grass cover crops like cereal rye generally attain greater dry matter and produce a better weed suppressive mulch than legume cover crops used with corn.

Regional Perspective and Constraints

Agriculture in the eastern region of the United States includes an array of relatively small farms averaging 73 ha per farm (National Agriculture Statistics Service [NASS] 2011). This region produces a diverse range of commodities in integrated and decoupled crop and livestock operations. Approximately one third of the landscape is used for agriculture, with animal production representing a significant segment of the agricultural industry (U.S. Environmental Protection Agency 2007). For example, in the Northeast alone there are more than 17,200 dairy farms and 1.4 million milking cows (NASS 2011; Winsten et al. 2010). The region as a whole is a net importer of nutrients in the form of grain for livestock feed and fertilizer for crop production (Anser and Townsend 1997). Arable land in the region spans five physiographic provinces, which vary considerably in both topographic features and climate. As a result, soils in the region range from droughty to poorly drained, are shallow and highly weathered, and have low organic matter content and low fertility compared to midwestern soils. Droughty summer conditions are more problematic in the sandy coastal plain soils than in the heavier soils of the Appalachian Plateau and Ridge and Valley physiographic provinces. These droughty conditions are also problematic when moving on a north to south gradient. Furthermore, droughty summers reduce yield potential, crop growth, and subsequently nutrient cycling. Due to steep topography and high precipitation, agricultural production in the eastern United States is prone to erosion and nutrient loading in sensitive estuarine environments such as the Chesapeake Bay. As a result, soil conservation is a priority in the region. Research, farmer innovation, and monetary incentives from federal programs have resulted in considerable interest in using cover crops to, in part, address the production challenges mentioned above. Cover crops have potential to enhance soil conservation in the region without impacting crop performance since spring soil moisture is typically not limiting (annual precipitation is 760 to 1012 mm, evenly distributed throughout the year). Furthermore, cover crop residues can increase crop tolerance to droughty conditions by lowering surface moisture evaporation.

Operationalizing Cover Crop Management

Although using cover crop residue as mulch to suppress weeds in no-till planted crops has been researched for decades, this approach was not considered to be feasible by organic grain growers until the development of the cover crop roller-crimper. This technology was first developed in South America (Derpsch et al. 1991). Early investigations into roller-crimper technology in the United States was conducted by USDA-ARS researchers in Auburn, AL (Ashford and Reeves 2003; Kornecki et al. 2006), and popularized by the Rodale Institute in Kutztown, PA. The primary manufacturer of the roller-crimper has been I&J Manufacturing of Gap, PA. Blueprints for the roller-crimper, which is made from a steel cylinder with metal slats welded perpendicular to the cylinder and arranged in a chevron pattern to reduce vibration, were also made available online for free, furthering the availability of the tool (see http://www.rodaleinstitute.org/no-till_revolution). This relatively inexpensive tool enables organic growers to terminate cover crops mechanically, without the use of herbicides. Several factors contribute to interest in roller-crimpers compared with other methods of terminating cover crops, such as mowing. Roller-crimpers can be operated at faster speeds and do not require an energy-intensive power take-off (PTO) drive, and thus require less fuel and labor. Weed suppression provided by cover crops terminated with the roller-crimper can also be greater than that provided by cover crops terminated with mowers. This is because mowers unevenly distribute cover crops residue and the residue decomposes faster after maceration (Creamer and Dabney 2002). More recently, engineers at USDA-ARS in Auburn, AL, have developed new roller-crimpers for both grain and raised-bed vegetable production (Kornecki et al. 2009).

Mechanical control of cereal rye is growth-stage dependent with greater than 90% control typically observed when rolled at the milk stage or later (Kornecki et al. 2006; Mirsky et al. 2009). Ineffective cereal rye termination will result in recovery, regrowth, or both and potential crop competition as well as viable seed production, which can contaminate winter cereal grain cash crops in the rotation. The direction of planting the cash crop must correspond to the direction of rolling to minimize hair-pinning and wrapping of residues and row cleaners (Kornecki et al. 2009). In addition, the rye should not be rolled in the same direction it was seeded because this can reduce the uniformity of soil coverage and the soybean planter units run the risk of lining up in the rows of rye reducing effective seed placement.

Weed Suppression from Cereal Rye

The necessity of using cover crops for weed suppression in reduced-tillage organic cropping systems highlights the importance of understanding the factors that influence this process. Cereal rye has been studied extensively over the last three decades for the physical and chemical attributes that contribute to its weed-suppressive capabilities (Barnes and Putnam 1983; Burgos et al. 1999; Mirsky et al. 2011; Teasdale and Mohler 1993). Under typical cover cropping practices across the eastern United States, cereal rye usually produces biomass levels of approximately 4,000 to 6,000 kg ha^{-1} when grown to maturity without an N fertilizer application, and as high as 10,000 to 12,000 kg ha^{-1} with optimal management (Mirsky et al. 2011; Reberg-Horton et al. 2012). Conventional growers often terminate rye at earlier growth stages when considerably less biomass has accumulated.

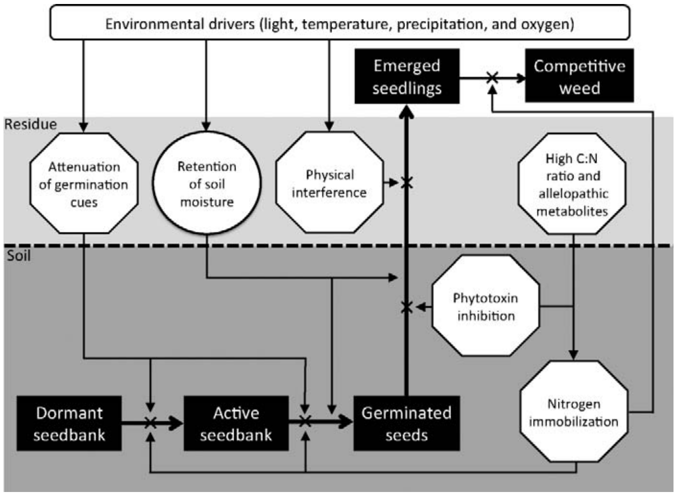

Figure 1. Schematic depicting the mechanisms for suppression or enhancement of weed germination and emergence by mulch from a cereal rye cover crop. Heavy solid arrows indicate weed life stage transitions. The lighter solid arrows indicate mulch induced factor effects that either inhibit or promote life stage transitions. Black rectangles connected by arrows represent weed life stages from dormant seeds to emerged seedlings. Octagons represent effects that inhibit weed life stage transitions at the point marked with an "X." Circles represent effects that enhance emergence at the points designated by the attached arrow.

Research with a range of surface rye mulch rates has shown that residue must be present in amounts substantially higher than these typical levels to effectively suppress annual weeds (Teasdale and Mohler 2000). For example, greater than 75% inhibition of the emergence of most annual weeds was obtained only when rye mulch biomass exceeded 8,000 kg ha^{-1} dry weight and mulch thickness exceeded 10 cm. The primary mechanisms by which cereal rye residues inhibit germination and emergence are by (1) attenuating environmental cues that break seed dormancy, (2) physically interfering with the emergence process, and (3) releasing phytotoxic compounds (Figure 1). Teasdale and Mohler (1993) showed that cereal rye residue can limit light and temperature cues that weed seeds often require for initiation of germination. Seeds that do germinate under high levels of mulch ($>$ 8,000 kg ha^{-1}) are inhibited primarily by physical interference of the mulch materials with the upward movement of emerging seedling and with the downward penetration of light to seedlings, whereby seed nutrient reserves are exhausted before seedlings reach sufficient light to become established. Release of phytotoxic compounds from cereal rye residue has been shown to inhibit weed germination and growth processes of many plant species, and the benzoxazinoid group of compounds have been identified as the most active compounds in cereal rye (Barnes and Putnam 1987; Macías et al. 2005; Reberg-Horton et al. 2005). Recent research suggests that benzoxazinoid compounds are not present in soil for more than 2 wk after rye termination and are found at concentrations too low to account for weed suppression (Rice et al. 2012). Thus, allelopathic effects that may occur are most likely caused by compounds other than benzoxazinoids. That said, physical rather than allelopathic influences probably predominate when mature cereal rye is terminated and used as a surface mulch (Teasdale et al. 2012).

The impact of cereal rye on soil inorganic N availability and the subsequent effects on weeds have not been as well characterized as the physical and allelochemical effects. The high biomass levels and residue quality (high C : N ratio, lignin, and hemicellulose content) of cereal rye results in very low inorganic N released to soil during residue decomposition and could contribute significantly to weed suppression by rye residue (Figure 1). Most nonleguminous weeds are highly responsive to N (Blackshaw et al. 2004; Henson and Jordan 1982; Tungate et al. 2006), and therefore manipulation of soil inorganic N levels could serve as a tactic for reducing weed competition in a cereal rye–mulched soybean cash crop. Frey et al. (2000) demonstrated (via ^{15}N tracer) fungal mediated upward movement of soil N from below the soil surface into the rye mulch. Research on exploiting niche differences and manipulating soil C : N ratio as a weed suppression tool is in its infancy, but some research suggests that it is effective and has multiple benefits (Phelan et al. 2008; Whitehouse et al. 2009). In a study of rolled rye vs. no-till plots without a cover crop mulch, soil inorganic N from plots with cereal rye was significantly lower in the surface to 10-cm throughout the duration of the growing season (Wells 2010). Immobilization of N played an important role in the continued suppression of available soil N, whereby available mineralized N from soil organic matter was quickly immobilized via fungi and bacteria. Beyond exhibiting classical N deficiency symptoms, weed shoot tissue N concentration was lower in the cereal rye–mulched treatments when compared to their no rye-mulch counterparts (Wells 2010). These results suggest that manipulating soil N with cereal rye mulch may play a larger role in weed suppression than previously thought.

Weed species vary widely in their sensitivity to cover crop residue, and the degree of sensitivity is mediated by soil edaphic features. Therefore, weed community structure and seed bank density will determine the success of cover crop–based weed management. Annual weed species with relatively smaller seed sizes are more sensitive to suppression by surface residue than larger seeded species (Mohler and Teasdale 1993; Teasdale and Mohler 2000). Mohler (1996) suggested that surface residue would inherently favor crops that have seed that is one to three orders of magnitude larger than seed of annual weeds. This selectivity between crops and weeds applies equally to differences in seed size among weed species and can be accounted for by greater nutrient and energy reserves in the endosperm of larger seeds to facilitate penetration of thicker mulch. In addition, larger seeds with greater energy and nutrient reserves may have greater metabolic capacity to detoxify allelopathic compounds or overcome a low N environment than smaller seeds. Perennial weeds with relatively large reserves and lower dormancy requirements than annual weeds can also be highly insensitive to or even stimulated by cover crop residue (Mirsky et al. 2011). Thus, regardless of the mass and thickness of residue achieved, weed species with little sensitivity to cover crop residue are likely to proliferate in a cover crop–based weed management system.

Table 1. Cultural practices that can be used to increase cereal rye biomass production.

Practice	Benefit	Drawback
Select high-biomass cultivar	Does not require management modifications	Availability of seed may be limited
Sow earlier in fall	Increased nutrient scavenging	Need to wait until preceding crop is harvested
Terminate later in spring	Improved control of cereal rye with roller-crimper	Reduced soybean yield potential
Increase sowing rate	May provide greater ground cover and weed suppression	Increased seed costs and response limited to low initial rates
Supplement fertility	May provide opportunity to spread manure	Increased costs and gives weeds competitive advantage over soybean
Irrigate	May improve soil microbial activity and ability to plant soybean	Infrastructure needed and response limited to dry conditions when water may need to be conserved

Factors Driving Cereal Rye Biomass and Their Interactions with Weeds

Cover crop–based weed suppression, as described, is greatly affected by biomass levels. Teasdale and Mohler (2000) concluded that cereal rye does not typically reach biomass thresholds necessary for consistent weed suppression and that mulches for weed suppression have primarily been used in vegetable production systems in which straw mulch can be augmented. In response to this work, numerous studies have examined agronomic management practices for the purpose of enhancing cereal rye biomass levels, including planting and termination date timing (Ashford and Reeves 2003; Mirsky et al. 2011; Nord et al. 2011), seeding rate (Boyd et al. 2009; Ryan et al. 2011a) and soil fertility (Mirsky et al. 2012; Ryan et al. 2011a). The effects of these agronomic practices on cereal rye biomass and subsequent weed suppression (Table 1) are discussed below.

Management Timing. Since cereal rye phenology is tightly regulated by thermal time (Mirsky et al. 2009), fall planting and spring termination of cereal rye will influence growth stage and biomass production. Therefore, management timing of cover crops can be used to maximize cereal rye biomass production. For example, in Pennsylvania, cereal rye planted at 10-d intervals from late August to mid-October and terminated at 10-d intervals from May 1 through May 30 ranged in biomass from 1,615 to 12,600 kg ha^{-1}. When cereal rye biomass accumulation was modeled on a thermal time basis (growing degree days), a 5–degree day difference in the fall was equivalent to a 1–degree day in the spring regarding rye biomass accumulation (Mirsky et al. 2011). After stem elongation (Zadoks growth stage 30), cereal rye can accumulate dry matter at a rate of 200 kg ha^{-1} d^{-1} under optimal growing conditions. Within this same experiment, total weed density decreased with increasing cereal rye biomass, which was influenced by both cereal rye seeding and termination date. Early-emerging summer annual weeds such as common lambsquarters (*Chenopodium album* L.) were less effectively controlled because their emergence is synchronized with lower cereal rye biomass levels (Mirsky et al. 2011). Late-emerging summer annual weeds tend to have emergence periods synchronized with maximum cereal rye biomass and are therefore more effectively controlled. Finally, perennial weeds were not affected by cereal rye mulch termination timing or biomass level, a relationship well documented in the literature (Facelli and Picket 1991; Mirsky et al. 2011; Mohler and Teasdale 1993).

These species-specific responses of weeds to cover crop management timing prompted closer evaluation of this relationship. In 2008 and 2009, follow-up trials were tested across two cereal rye sowing dates and three cereal rye termination dates. Seeds of three summer annual weed species with known differences in emergence periodicity were added to microplots to evaluate the interplay between cereal rye termination date and weed emergence periodicity. Common ragweed, giant foxtail (*Setaria faberi* Herrm.), and smooth pigweed (*Amaranthus hybridus* L.) seeds were each added to microplots at 100, 450, or 1,050 seeds m^{-2} the previous fall after rye establishment. As hypothesized, delaying cover crop termination reduced common ragweed biomass when pooled over cereal rye sowing dates, which was a result of increased cereal rye biomass with later termination. This finding supported previous results (Mirsky et al. 2011) as well as the notion of delaying termination to maximize weed suppression. However, when we controlled for cereal rye biomass and compared early sowing and early termination to late sowing and late termination, total weed biomass was reduced with earlier cereal rye termination. In both years, these pairs of treatments resulted in approximately 8,000 to 9,000 kg ha^{-1} cereal rye biomass at termination. When pooled over years and weed seed densities, weed biomass was reduced by approximately 44% when cereal rye was sown and terminated early, compared to late. In both years and across all treatments, common ragweed was the dominant weed species. Cereal rye ground cover in the spring increases proportionately with earlier sowing in the fall, which also results in earlier maturation in the spring. The combined effects of increasing early spring ground cover and early termination of cereal rye appears to enhance weed suppression. Thus, because the roller-crimper does not control emerged weed seedlings, it appears that preempting emergence of common ragweed and other early-emerging species by planting cereal rye early and terminating relatively early can be beneficial if cereal rye biomass and control with the roller-crimper are not compromised.

Increasing Cereal Rye Seeding Rate. Results from a factorial experiment comparing different seeding rates that was conducted in Maryland and Pennsylvania in 2008 and 2009 showed that increasing cereal rye seeding rates could effectively increase weed suppression. When averaged across all site-years, increasing cereal rye seeding rate from 90 to 210 kg seed ha^{-1} significantly decreased weed biomass by 31% (Ryan et al. 2011a). Interestingly this increase in weed suppression was not due to increased cereal rye biomass at termination, but rather was attributed to increased ground cover early in the spring. These results prompted experimentation with several modifications to our cereal rye seeding approach for cover crop–based organic rotational no-till soybean. First, these results confirmed that using relatively high cereal rye seeding rates is justified despite the lack of effect on cereal rye biomass. Second, they led to the practice of using a dual seeding method approach in which a portion of the seed is broadcast and the remainder is drill seeded. The drill disturbs the soil surface and results in soil being moved into the interrow region. This strategy is thought to increase ground cover by filling interrow spaces with broadcasted seed, providing a balance between the consistency achieved with drill-seeding and the soil coverage achieved with broadcast seeding. Although the potential benefits of this approach has not been quantified, several research programs have adopted it as a best management practices for cereal rye establishment. The additional seed and tractor costs associated with dual seeding has to be weighed against potential improvements in weed suppression.

Increasing Soil Fertility. Cereal rye biomass production can be significantly constrained by soil fertility levels, particularly available N. At anthesis, shoot N concentration of cereal rye is typically between 9 and 11 g N kg^{-1} (Graham et al. 1983; Shipley et al. 1992), and thus 10,000 kg of rye biomass ha^{-1} requires at least 90 to 110 kg of available N ha^{-1}. Cereal rye is recognized for its ability to proficiently scavenge residual inorganic soil N left in the soil from the previous season (Adeli et al. 2011). In regions with high soil organic matter content and cool, moist climates, residual N levels are likely sufficient to support optimum cereal rye biomass production. This is especially true of soils with a history of manure and legume cover crop use (Power and Doran 1984; Spargo et al. 2011). However, where residual soil inorganic N and/or mineralizable N levels are low, it may be necessary to fertilize cereal rye in order to produce biomass levels high enough to effectively suppress weeds.

In order to maximize N use efficiency and minimize residual N after cereal rye termination, it is important to target the period of highest N demand, which for cereals is between Zaddoks growth stage (GS)-30 and GS-60. Therefore, any supplemental N applied must be at or prior to GS-30 (stem elongation). This can be challenging with organically approved materials with low levels of soluble N. Many sources of N in organic systems also include P (e.g., dairy manure and poultry litter) that can constrain their use if nutrient management is a concern. The development of in-season indicators to predict cereal rye biomass potential, N demand, or both would better facilitate efficient N fertility management. Tiller density at GS-25 has been used as an effective predictor of fertilizer N need for wheat (Scharf and Alley 1993; Weisz et al. 2001) and may prove equally useful for cereal rye. In an ongoing experiment, we found that tiller density at GS-25 explained 58 and 66%, respectively, of the variability in rye biomass at GS-60 (Mirsky et al., unpublished data). Nitrogen management strategies that consider fertility source and temporal N demand must be developed in order to ensure efficient resource use and limit the reactive N load on the environment and subsequent weed populations.

Cereal Rye Germplasm: Traits of Interest

Cereal rye has not been explicitly bred to deliver any of the potential ecosystem services that are provided in this reduced-tillage organic system. This cereal has been bred for both forage use and as a grain crop. Key traits that would be desirable for use in our reduced-tillage organic system include a more moderate height or stronger stems that would lessen the amount of lodging (management constraints from lodging discussed below); greater allelochemical content (Reberg-Horton et al. 2005), which can also slow residue decomposition (Wagger et al. 1998); rapid early canopy development; and maturation times that match the desired planting dates for each region (Reberg-Horton et al. 2012). Breeding is more difficult with cereal rye than other small grains. As an obligate outcrosser, selfing is not possible and breeding approaches such as half-sib mating must be employed. Height and maturation time are highly heritable and easy to select for. Less is known about the heritability of allelochemical content, though substantial variation is believed to be present based on wheat (Wu et al. 2000); however, limited screening of rye germplasm has occurred (Reberg-Horton 2005). The demand for these desirable cover crop traits must increase to justify any future public or private breeding effort with cereal rye or other cover crops.

Soybean Planting Equipment Challenges

The high levels of cereal rye biomass required for persistent weed suppression can constrain soybean seed placement. Having equipment that can adequately plant soybean seed through high levels of cereal rye mulch is critical for soybean production success. In this cover crop–based system, soybean seed placement requires partial or full cutting of rye residue since the rolled cover crop can lay down in multiple angles when lodging occurs prior to rolling. As a result, planter and drill technology must be equipped with the appropriate coulters, planting unit gauge wheels, row cleaners (available on planters only), weight, and effective closing wheels to ensure accurate seed placement. In addition to working with the proper equipment for high-residue crop production, coordinating management decisions based on soil moisture levels may improve crop establishment and performance. The following subsections within this equipment section represent the evolution in planting technology used by the authors over the past 10 years. We summarize both unpublished data as well as information gathered through trial and error. The proper configuration of soybean planters and drills cannot be overstated because good soybean populations are necessary for not only maximizing crop yield but also minimizing weed competition.

Planters vs. Drills. There are trade-offs to using drills vs. planters for soybean planting into high levels of cereal rye biomass. Based on our experience with high cereal rye biomass levels, planters provide more consistent soybean populations compared to drills due to lower cutting resistance and greater precision with both seed metering and depth control. Even on drills with dual tool bars, there is less space between planting units, which limits options for residue management (i.e., row

Table 2. A decision framework for soybean row spacing, equipment type (drill or planter) and use of high-residue cultivation based on experimentation by authors.

	Cereal rye biomass levels	
Weed seed bank density	Low (3,000 to 6,000 kg ha^{-1})	High (7,000 to 12,000 kg ha^{-1})
Low	Drill	Splitter
High	Planter with cultivation	Splitter or planter with cultivation

cleaners). The amount of possible down pressure per row is also less for drills due to the increased number of rows. However, reducing the time necessary for soybean canopy closure through narrow crop row spacing is an important cultural practice that aids in weed control (Hock et al. 2006). When possible, equipment selection should be based on cereal rye performance in a given year (Table 2). When rye biomass levels are moderate (4,000 to 6,000 kg ha^{-1}), a no-till drill can achieve good seed placement (Mirsky, unpublished data). As biomass levels increase, we find planters provide a better option. Configuring planters with split-row units to plant on a 40-cm row spacing may provide the best alternative (Reberg-Horton, personal communications).

Equipment Weight. Planting soybean into thick cereal rye mulch requires heavy-duty downforce springs or a pneumatic downforce system. With dry conditions, even greater downward force is required to penetrate through both the rye and soil to get adequate seed placement. Planters may need extra weight mounted on the frame. Smaller planters and drills (research plot or small farm scale; 3 m wide or less) have more difficulty with this problem due to their lower weight, while heavier equipment can be an advantage (Curran, personal communications). On heavier-textured soils (silt loam) in Pennsylvania and Maryland, 136 kg of weight is routinely added on each planter row unit using bags of sand or seed or steel weights in order to get sufficient soil penetration under drier conditions. Other planter modifications can include frame mounting one or two large (approximately 567 L) poly tanks that can be filled with water to increase planter weight.

Coulters. The type of coulters used on a drill or planter plays a critical role in ensuring good seed placement. On no-till planters and drills, the coulter functions to cut residue and prepare a better seedbed prior to the disk openers. For both drills and planters, several coulter types are available. In our work, we have relied primarily on lightly fluted to straight-edged coulters that are designed for residue cutting and soil penetration. We find wave or turbo-type coulters are less desirable due to their higher cutting surface area that often leads to hair-pinning of residue or ineffective cutting. Furthermore, such coulter types can result in greater soil disturbance that stimulates weed germination. Even, light fluting is a compromise between residue cutting ability and seedbed preparation. In high-residue environments, straight coulters or bubble coulters are more effective at cutting residue but cause more sidewall compaction (Reberg-Horton, personal communications). In our work, we have used no-till drills equipped with an integrally mounted coulter to cut residue and prepare a mini-seedbed.

Row Cleaners. Row cleaners can help improve stand establishment in heavy residue. In Pennsylvania, a 25% increase in soybean population was observed when using row cleaners in contrast to using the same planter without row cleaners (Mirsky, unpublished). Increased populations and faster emergence time resulted in either no difference in weed biomass or up to a 70% reduction (decrease by 700 kg ha^{-1}). That said, cover crop residue could wrap around the wheels of residue managers and reduce their usefulness. Although residue managers can improve crop stand, they also move the weed-suppressive cover crop mulch away from the crop row that is critical for weed control in organic no-till.

Closing Wheels. The type of closing wheel and mechanisms for downward pressure are particularly important in high-residue environments where it is more difficult to get adequate furrow closure and resulting seed-to-soil contact. Even with the heaviest of closing wheels, sealing the slit can be difficult at times and particularly under moist soil conditions. Poor furrow closure can not only reduce germination and emergence due to more extreme micro-climatic conditions, but also leave seeds and seedlings vulnerable to birds and other pests, which can severely reduce populations. Spading or spiked closing wheels rather than solid types can help close the seed slit in wet soils. In Beltsville and at Penn State, we have also used a single 38-cm spiked closing wheel alongside a smooth cast closing wheel on each row unit to help improve slit closure. Site-specific evaluations of closing wheels, down pressure configurations, and adjusting depth-gauge wheel settings, in different cover crop and soil moisture situations, can greatly improve soybean establishment and stands.

Management Timing and Crop–Soil Interactions. Beyond mechanical factors, soil and plant moisture greatly influences crop seed placement and establishment through high-residue mulches. In work by Nord et al. (2011), that included both a planter and a drill across five different soybean planting dates in the spring with increasing amounts of rye biomass, soybean stand differences were not linearly related to termination date as expected. Rather than being influenced solely by mulch biomass, soybean stand may have been more influenced by differences in rainfall patterns and subsequent soil moisture that, in turn, influenced planter or drill penetration, seed placement, and furrow closure. In additional work by Mischler et al. (2010), soybean populations were reduced in later terminated rye at one location presumably due to greater amounts of residue, while dry weather during an earlier planted treatment made it more difficult to achieve consistent soybean populations at another location. Such variability in soybean stand density between termination dates suggests that the technical challenges of planting into a thick layer of cover crop mulch are not trivial. We outline several important factors to consider.

The optimal timing of termination of cereal rye with a roller-crimper relative to planting soybean appears to be linked to regional factors. Delaying soybean planting by several days after rolling can allow the cereal rye to recover. The regrowth or recovering rye will often not grow parallel to rolling, thus requiring more extensive residue cutting with the planter or drill. Rolling and planting on the same day is attractive in regions with ample spring moisture. This approach allows the rolling and planting to occur simultaneously with the roller-crimper either mounted to the front of the tractor and the planter or drill to the rear, or both implements in the rear with the toolbars connected. Based on our experience, another advantage to a single roll/plant operation is that fresh plant material is easier to cut than aged surface residue. This is particularly true when aged surface mulches are wet. In drier locations or on sandier soils, rolling and allowing soil moisture to be replenished by precipitation is advised (Price et al. 2009). Several investigators recommend killing cover crops well before planting to allow precipitation to rebuild soil moisture (Hargrove and Frye 1987; Price et al. 2009; Reeves 2003). The delay in management can have ancillary benefits; Hammond and Cooper (1993) suggested no-till planting approximately 14 d after killing cereal rye to avoid seedcorn maggot damage in soybean. While our research team has not tested this practice, other authors have suggested planting first and rolling later because it does not require a high performance no-till planter (Bernstein et al. 2011). The authors find it generally more important to let soil moisture drive the timing of planting. Therefore whether roll/planting or roll-roll/plant, we time operations with a rain event to get maximum soybean establishment.

Potential for a Synergistic Interaction between Rye Residue and Soybean Population

We tested the effects of combining two cultural management practices for improving weed suppression in organic soybean no-till planted into a rolled-crimped cereal rye cover crop (Ryan et al. 2011b). We used a factorial design to test for an interaction between the practices of increasing soybean planting rate and increasing cereal rye mulch, both of which can be accomplished by various means described above. Soybean was no-till planted at 0, 19, 37, 56, and 74 seeds m^{-2} and cereal rye residue was applied at five different rates representing 0, 0.5, 1, 1.5, and 2 times the normal rate (5,000 to 8,500 kg ha^{-1}). We hypothesized that the mulch would delay weed emergence, while allowing the soybean, with a larger seed size relative to weeds, to emerge first and develop a relatively more competitive leaf canopy. We observed a synergistic interaction between practices in two of the four site-years. This interaction occurred because increasing soybean density did not affect weed biomass in the absence of rye residue; however, when sufficient rye residue was included, increasing soybean density resulted in a decrease in weed biomass. Optimum weed suppression and yields were consistently observed when cereal rye biomass was 8,000 kg ha^{-1} and soybean was planted at the highest rate (740,000 seeds ha^{-1}). At very high mulch rates, soybean yield declined because of poor stands. This is an important example of how a synergistic interaction between two complementary cultural practices can be exploited for enhanced weed management in cover crop–based organic rotational no-till soybean production.

High Residue Cultivation

Despite the best cover crop management, high weed seed bank densities and perennial weed infestations constrain the success of the cover crop–based system. While crop rotation management is necessary for reducing weed seed banks and suppressing perennial weeds, high-residue cultivation is a viable option in cover crop–based organic rotational no-till. Results from several recent experiments illustrate the utility of high-residue cultivators for supplemental weed suppression in organic no-till planted soybean (Nord et al. 2011). High-residue cultivators are generally characterized by the presence of a coulter in front of the cultivator shank to cut through mulch, along with a relatively flat cultivator sweep that severs weed shoots from their roots just beneath the soil surface with minimum disturbance to the residue (Bowman 1997). Earlier research on inter-row high-residue cultivation was less successful because of excessive soil disturbance and antagonism between surface residue and cultivation efficacy (Teasdale and Rosecrance 2003). However, improvements to high-residue cultivators that minimize soil disturbance and better slice through surface residue have increased their utility. We conducted experiments in Beltsville, MD; Kutztown, PA; Raleigh, NC; and Rock Springs, PA to test the effects of using a high-residue cultivator for supplemental weed control in organic no-till planted soybean. Results showed that weed biomass can be five times higher in uncultivated soybean than when cultivated (Table 3). However, the effects of high-residue cultivation on yields have been mixed. High-residue cultivation increased yields, particularly when weed biomass was high. However, reductions in weed biomass did not consistently result in increased crop yields. High-residue cultivators do not always kill weeds, but instead slow their growth and subsequent impact on yield. Furthermore, untimely high-residue cultivation can kill weeds after the competitive effect on the crop has already been realized. The result would be differences in weed biomass but less of an impact on yield. Future work should investigate the effects timing of high-residue cultivation has on weed–crop competition and when it is economically beneficial to cultivate.

Integrating No-Till Soybean into Existing Rotations

The research described in this paper defines a potentially viable rotational no-till system for organic soybean production that has proven effective in short-term experiments. Challenges still remain in determining the best fit for this system in long-term field crop rotations. Typical field crop rotations could include corn–soybean, corn–soybean–wheat, and corn–soybean–wheat–3 yr alfalfa (*Medicago sativa* L.). Therefore, cropping system integration of rotational no-till soybean is constrained by several factors, including timing of previous cash crop harvest (i.e., corn) to ensure timely cereal rye establishment and timely soybean planting for successful subsequent small grain or cover crop establishment. As a result, evaluation of the rotational no-till soybean system within a long-term crop rotation is necessary to confirm

Table 3. Cereal rye biomass, weed biomass, density, or cover and crop yield improvement across four sites on the eastern United States including Pennsylvania State University (Rock Springs, PA); USDA-ARS (Beltsville, MD); The Rodale Institute (Kutztown, PA); and North Carolina State University (Raleigh, NC). Values within parentheses are standard errors of the mean.

			Weed biomass, density, or cover		
Site	Years	Cereal rye biomass	Uncultivated	Cultivated	Crop yield improvement
		kg ha^{-1}			%
Beltsville, MD	2009	7,012 (376)	1,952 (465)	674 (260)	39
Rock Springs, PA	2009	7,722 (451)	1,601 (234)	974 (223)	NS*
	2010	7,548 (483)	1,883 (280)	859 (144)	NS
	2011	6,719 (225)	30 (25)	41 (5)	NS
	2011	1,674 (650)	1,933 (211)	1545 (9)	54
Kutztown, PA	2010	10,608 (630)	893 (225)	139 (70)	23
	2011	5,974 (473)	2,887 (563)	1,525 (303)	18
		% cover or weed density (plants m^{-2})			%
Raleigh, NC	2008	6,606	61%	44%	NS
	2009	8,066	1.2	0.99	NS
	2009	8,366	0.13	0.006	NS

* Abbreviation: NS = not significant.

optimal, regionally specific crop and cover crop management timing.

Integration of rotational no-till soybean production into organic grain rotations also requires increasing soil N mineralization levels for adequate cereal rye biomass production. This is increasingly important when crop production is on coarser textured soils or those with low soil organic matter levels. Nitrogen availability and its management result in trade-offs between producing optimal weed suppressive mulches and minimizing weed performance. As stated previously, low N availability will impact weeds, but to a greater extent the cover crop biomass required for weed suppression. Insufficient N for adequate rye biomass production may be particularly problematic during the transition phase to organic when soil organic matter may be relatively low. During this stage, supplemental N may be warranted to ensure adequate rye growth. However, organic farms can build soil organic levels significantly over time, meaning more N could be available for rye cover crops on farms that have been organic longer. Building up soil mineralization potential is important because most growers would not consider fertilizing their cover crops. However, higher N mineralization from soil may also impact the weed-suppressive ability of the cereal rye mulch by overcoming the duration of N immobilization from the surface mulch. Furthermore, the magnitude of these effects is going to depend on soil and crop management history (Mallory and Friffin 2007).

Lastly, using a multitactic approach to weed management will be critical to the success of cover crop–based organic rotational no-till soybean production. As part of a holistic systems approach, mechanical tactics should be integrated with cultural weed management practices. The identification of synergistic interactions between cultural practices, as discussed for rye residue and soybean population, is particularly important for designing effective weed management for organic agriculture. Embedding this no-till organic soybean system within a suitable crop and tillage rotation is particularly important to realizing the potential benefits of this system. Use of a phenologically diverse crop rotation has been shown to be particularly important for reducing the weed seed bank (Teasdale et al. 2004) and increasing crop yields (Cavigelli et al. 2008) in organic grain production. Multitactic weed management would be most effective when weed seed bank densities are low, but would be critical when densities are high, requiring sequences of cultural and mechanical practices to be implemented in combination to drive down weed seed banks. Equally important would be rotational use of tillage during selected cropping sequences to disrupt weed species favored by absence of tillage (e.g., perennials) as well as permit incorporation of organic amendments and facilitate planting smaller-seeded crops such as forages.

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