Rowcovers and Strip Tillage Provide an Alternative to Plasticulture Systems in Summer Squash Production

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Abstract. Plastic mulch is often used in cucurbit production, but it has negative soil health and environmental implications due to use of tillage for installation and generation of plastic waste. This 2-year study aimed to find a viable alternative to plastic mulch through the use of strip tillage and rowcovers, as rowcovers could help minimize yield loss from strip tillage by providing warmer air and soil as well as providing insect protection. A split-plot design was used in both conventionally and organically managed summer squash (Cucurbita pepo), with production system as the whole-plot factor [conventional tillage with black plastic mulch also referred to as plasticulture (PL) and strip tillage into rolled cereal rye (Secale cereale) (ST)] and rowcover use as the subplot factor (rowcover until anthesis or no rowcover). Rowcovers reduced the incidence of squash vine borer (Melittia cucurbitae) and eliminated the need for insecticide sprays to control this insect pest, but did not reduce the incidence of yellow vine decline or the sprays needed to control squash bug (Anasa tristis). Rowcovers increased average air temperature by 1.6 to 4.0 °C and increased maximum air temperature by up to 10.3 °C. Rowcovers decreased average light intensity by 33% to 39%. Though soil temperature in PL tended to be higher than in ST, in 1-year rowcovers helped bridge the gap. Plant biomass was consistently higher in the PL than the ST system. Averaged across rowcover treatments, plants in PL had higher marketable yields than those in ST; however, the use of rowcovers often led to comparable yields between the production system treatments. Rowcover was a significant factor explaining marketable yield for the organically managed fields both years. There was no consistent effect of production system on soil microbial biomass carbon (MBC). Based on our results, strip tillage into rolled rye could be a viable alternative to plasticulture for summer squash production in Iowa, and rowcovers could help increase yields in ST especially in an organic management system.

Plastic mulch is commonly used by commercial producers of cucurbits because it increases soil temperature, reduces weed pressure, retains soil moisture, and increases earliness of harvest (Lamont, 2005). Compared with bare ground systems, black plastic mulch can increase yields of cucumber (Ibarra-Jiménez et al., 2004), muskmelon (Ibarra et al., 2001), and summer squash (Mahadeen, 2014). However, there are concerns about environmental sustainability due to the generation of plastic waste (Hemphill, 1993) and the disturbance to the soil from intensive tillage during installation. Bio- and photodegradable film mulches address the issue of waste, but they are expensive (Cirujeda et al., 2012), may not decompose at the proper time (Kasranj and Ngouajio, 2012), and do not eliminate the need for intensive tillage. Tillage degrades soil structure (Magdoff and van Es, 2009; Peigné et al., 2007), thereby increasing susceptibility to compaction, and can decrease soil microbial biomass (Karlen et al., 2013), soil moisture (Hoyt et al., 1994), and earthworm diversity (Pelosi et al., 2014).

Crop covers are often used to build soil health by reducing soil erosion and increasing soil organic matter, but they must be managed so they do not compete with the main crop (Reberg-Horton et al., 2012; Snapp et al., 2005; Teisdale, 1996). One common approach is to incorporate the cover crop into the soil through tillage. This adds organic matter to the soil, but again, it leaves the soil vulnerable to erosion (Dickey et al., 1983) among its other potential negative consequences described earlier.

One way to end cover crops without tillage is to use a roller crimper, which is a tractor-mounted implement with a water-filled rolling drum, typically 3 to 4.5 m wide and having 0.6 m diameter that mechanically ends a cover crop by crimping the stems while leaving the root system and soil undisturbed (Parr et al., 2011). The rolled and crimped residue is then left intact on the soil surface to serve as biological mulch that can be used as an alternative to plastic mulch. This technique can be adapted to a strip tillage system by minimally disturbing one narrow strip for planting, leaving the mulch between rows undisturbed. Soils covered with heavy residue may be cooler than bare soil (Schonbeck and Evanylo, 1998), and residues on the surface can prevent weeds (Leavitt et al., 2011) and sustain soil moisture (Schonbeck and Evanylo, 1998). Reberg-Horton et al. (2012) also reported significant weed control using cover crop mulches; however, to achieve high levels of weed control it is imperative to obtain substantial cover crop biomass. Rolled cover crop systems can lead to yields equivalent to those of tilled, bare ground systems for pumpkin (Wyenandt et al., 2011), organic bell pepper (Delate, 2008), winter squash (Hoyt, 1999), and tomato (Hoyt, 1999). However, Leavitt et al. (2011) found that tomato, zucchini, and bell pepper in a no-till rolled cover crop system in Minnesota had lower yields than in a conventionally tilled system without cover crops, potentially due to the cool northern U.S. climate. These mixed results indicate the need for a technique to mitigate the potential yield loss when using a rolled cover crop system as opposed to bare ground.

Given the increased yields in plasticulture systems compared with bare ground, little work has been done comparing conventional management using plastic to systems that reduce tillage through low-disturbance alternatives such as strip tillage, especially in warm-season crops like cucurbits. One way to overcome the possible yield loss in a rolled cover crop system is to use rowcovers. Rowcovers can increase air temperature and soil temperature (Ibarra et al., 2001) and have been shown to increase yield of muskmelon (Cline et al., 2008), cucumber (Nair and Ngouajio, 2010), and watermelon (Soltani et al., 1995). By physically preventing insects from reaching young plants, rowcovers can prevent damage from insect feeding and reduce the spread of insect-transmitted pathogens like Erwinia trachephiila (Saalau Rojas et al., 2011). This pathogen is spread by spotted and striped cucumber beetles (Diabrotica undecimpunctata and Acalympna vitatum) and causes cucurbit bacterial wilt, a devastating disease for cucurbits growers. Another important insect-transmitted disease, yellow vine decline, is caused by Serratia marcescens, a pathogen spread by squash bugs (Bruton et al., 2003).

We had two primary objectives: 1) determine if using rowcovers in a strip tillage system can produce equivalent summer squash yield to a plasticulture system and 2) evaluate differences in yellow squash growth and yield with...
or without spundboned rowcovers and microclimate modifications that come along with rowcover use. We compared two production systems [conventional tillage with black plastic mulch (PL) and strip tillage into rolled cereal rye (ST)] with and without the use of rowcovers in organically and conventionally managed fields of summer squash. We evaluated these practices in two management systems (organic and conventional) due to the increased interest in using ST system by organic vegetable growers and growing number of conventional growers who have started valuing the importance of cover crops and view it as a tool to improve soil organic matter and a transitional tool to be more sustainable in their production. Conducting this research in both production systems allows for a wider impact over a large number of cucurbit growers.

Materials and Methods

Experimental site

Trials were conducted in fruitfield coarse sand (sandy, mixed, mesic Entic Hapludolls) at the Muscatine Island Research and Demonstration Farm in Fruitland, IA (lat. 40°12′15” N, long. 91°08′08” W). The 2013 field had previously been in sorghum sudangrass, and the 2014 field had previously been in a corn/soybean rotation under conventional management.

Planting material

For the conventionally managed field, ‘Li- oness’ yellow summer squash seeds (Seedway, Hall, NY) treated with thiaramidoxam, azoxy- strobion, mfenoxam, and fludioxonil were sowed into 72-cell trays with potting mix (Metro Mix 360; Sun Gro Horticulture, Agawam, MA). Untreated ‘Lioness’ yellow summer squash seeds were sowed with organic potting mix (Mix no. 11; Beautiful Land Products, West Branch, IA) into 72-cell trays for the organically managed field.

Experimental design and treatments

A split-split plot complete block design with four replications was used for both organically and conventionally managed fields, with a 3.7-m buffer area between the fields. Within each management system (organic or conventional), the whole-plot factor was production system [strip tillage into rolled cereal rye (ST) or conventional tillage with black plastic mulch (PL)] and the subplot factor was rowcover use (rowcover or no rowcover). Spacing between rows was 1.8 m. A guard row separated the split-plot treatments. Each subplot experimental unit consisted of 18 plants in one 9.5-m row, and each whole plot consisted of two subplots per guard rows

Land preparation

Tying of field operations is summarized in Table 1. Cereal rye (variety not stated) was seeded with a drill across all fields in October before each field season. In 2012, cereal rye was drilled at 56 kg ha⁻¹. Due to an insufficient stand of rye in Spring 2013, the Oct. 2013 seeding rate was increased to 123 kg ha⁻¹. Cereal rye in PL treatments was mowed and tilled in May. Plots were again tilled in June before laying black plastic mulch (0.02 mm thick) using a raised bed plastic mulch layer (Holland Transplanter Model 1275; Holland Transplanter Co., Holland, MI) that creates a 0.7-m-wide raised bed with drip tape (0.3 emitter spacing, 0.028 L·s⁻¹·30.5 m⁻¹) underneath the plastic.

Table 1. Field operations for the 2013 and 2014 summer squash trials in Fruitland, IA.

| Operation                  | 2013       | 2014       |
|----------------------------|------------|------------|
| Cereal rye drilled         | 12 Oct. 2012 | 2 Oct. 2013 |
| Rye strip tilled (in ST)   | —          | 8 Apr.     |
| Squash seeded in 72-cell trays | 9 May     | 14 May     |
| Rye mowed and tilled (in PL) | 9 May     | 29 May     |
| Rye crimped at anthesis (ST) | 22 May   | 29 May     |
| Rye strip tilled (in ST)   | 3 June     | 29 May     |
| Soil tilled and plastic laid (in PL) | 3 June     | 5 June     |
| Squash transplanted, rowcovers laid | 4 June   | 5 June     |
| Rowcovers removed          | 26 June    | 1 July     |

*ST = strip tillage into rolled cereal rye.
*PL = conventional tillage with black also referred to as plasticulture.
(Entrust SC; Dow AgroSciences) and pyrethrin (PyGanic EC50; McLaughlin Gormley King Co., Minneapolis, MN), and were controlled in the conventionally managed fields using permethrins (Pounce; FMC Corporation and Asana; DuPont, Wilmington, DE). Powdery mildew was treated with sulfur (Microtiol Dispers; United Phosphorus, King of Prussia, PA) and neem oil (Trilogy; Certis USA, Columbia, MD) in the organically managed fields, whereas mycelotubanil (Rally 40WSP; Dow AgroSciences) was applied in the conventionally managed fields. Plants were hand weeded after rowcover removal in 2013, and no weed- ing was needed in 2014. In 2013, the entire conventionally managed field was sprayed with a grass herbicide (Poast; BASF Corporation, Research Triangle Park, NC) on 9 July.

Data collection

Environmental monitoring. Hobo pendant temperature/light sensors (Onset Computer Corporation, Bourne, MA) were attached to wooden stakes placed in direct sun within the row, 15 cm above the soil surface, in all treatments in three of the four replications in the conventionally managed field, with one sensor for each experimental unit. They recorded air temperature and light intensity every 30 min throughout the growing season. Hobo pendant temperature sensors were bur- ened within the row, 15 cm below the soil surface, in all treatments in three of the four replications in the conventionally managed field, with one sensor for each experimental unit. They recorded soil temperature every 60 min throughout the growing season. Environ- mental monitoring occurred solely in the conventional fields because the differences in management systems (conventional and organic) in our experiment would likely not affect air or soil temperature.

Plant measurements. A SPAD meter (SPAD 502 Plus; Konica Minolta Sensing Americas, Ramsey, NJ) was used to measure leaf chloro- 

phyll content on 15 July 2013 and 12 Aug. 2014. Three soil cores (3.8-cm diameter, 15-cm depth) were taken within the row in each plot to make one composite sample per plot. Soil was kept in a sealed bag in a cooler at 4 °C until analysis. Soil samples were sieved using a 2-mm sieve. The sieve size was deemed appropriate instead of a more common 8-mm sieve (Karlen et al., 2013; Vance et al., 1987) because the sandy texture of the soil made it easy to sieve without much disturbance to the soil even with a smaller mesh size. MBC was extracted using a chloroform fumigation extraction method with a procedure modified from Vance et al. (1987). In 2013, extracts were analyzed on a Phoenix 8000 ultraviolet-Per-Sulfate Total Organic Carbon (TOC) Analyzer (Teledyne Tekmar, Mason, OH). In 2014, a Torch Com- bustion TOC/TN Analyzer (Teledyne Tekmar) was used. A conversion factor of 0.33 was used when calculating MBC.

Statistical analysis

Data were analyzed using PROC GLIMMIX and PROC MIXED of SAS (Version 9.3; SAS Institute, Cary, NC). Years and man- agement systems (organic and conventional) were analyzed separately. Replication was treated as a random factor. Mean separation was performed by “lsmeans” and “pdiff” statements using the Satterthwaite method. Percents of insect and disease incidence were transformed using arcsin square root. Unpro- tected least significant difference was used, thereby allowing for comparisons among treat- ments even without significant main effects or interactions. This was important because the main research question was not about the whole-plot or subplot treatments themselves, but about how they interacted.

Results

Weather. Monthly rainfall during the 2013 and 2014 growing seasons was similar to the 20-year average (Table 2), except for lower than average rainfall in July and Aug. 2013. Average monthly growing degree days (GDDs) were similar to the 20-year average, with fewer GDDs in July both years.

Air temperature and light intensity. In 2013, rowcovers did not affect minimum air temper- ature, but they increased mean air temperature by 3.1 to 4.0 °C and increased maximum air temperature by 6.2 to 10.3 °C (Table 3). In 2014, rowcovers increased minimum air tem- perature during the early season period by 1.4 °C. Similarly to 2013, rowcovers increased mean air temperature in both season periods by 1.6 to 2.6 °C. Rowcovers increased maximum air temperature in the early season by 5.4 °C but had no effect in the midseason period.

Rowcovers decreased average daily mean light intensity by 33% to 39% and decreased maximum light intensity by 34% to 44%, depending on the year (Table 4). The weight of rowcover used in this experiment is expected to have 70% light transmission

| Table 2. Monthly total precipitation and average growing degree days during the 2013 and 2014 growing seasons and the 20-year average at the Muscatine Island Research and Demonstration Farm in Fruitland, IA. |
|-----------------|-----------------|-----------------|-----------------|
| **Month** | **Monthly precipitation (mm)** | **Monthly avg GDD** |
| **June** | 154 | 125 | 136 | 345 | 375 | 362 |
| **July** | 75 | 116 | 88 | 391 | 356 | 426 |
| **August** | 0.5 | 107 | 104 | 386 | 398 | 403 |
| **Table 3. Average daily minimum, mean, and maximum air temperature in conventionally managed summer squash in 2013 and 2014 before rowcovers were removed, averaged across production system treatments, at the Muscatine Island Research and Demonstration Farm in Fruitland, IA.** |
| **Early season** | **Midseason** |
| **Treatment** | **Min** | **Mean** | **Max** | **Min** | **Mean** | **Max** |
| **Rowcover** | 16.3 | 28.9 | 49.8 | 18.6 | 32.6 | 52.8 |
| **No rowcover** | 15.7 | 24.9 | 39.5 | 18.0 | 29.5 | 46.6 |
| **P value** | 0.208 | <0.0001 | <0.0001 | 0.210 | <0.0001 | <0.0001 |
| **Rowcover** | 14.9 | 27.0 | 46.4 | 19.8 | 29.6 | 46.5 |
| **No rowcover** | 13.5 | 24.4 | 41.0 | 18.8 | 28.0 | 44.0 |
| **P value** | 0.007 | <0.0001 | <0.0001 | 0.129 | 0.022 | 0.149 |

*Early season: 5–15 June 2013, 6–16 June 2014.
*Midseason: 16–25 June 2013, 25–30 June 2014.

*P values based on F test. 
*A strong storm on 17 June 2014 disrupted a number of sensors. Those sensors were repositioned 24 June 2014. Data from 17 to 24 June 2014 have been discarded.
when new, but the rowcovers used in this experiment had been used in previous seasons as is the typical practice for most growers using rowcovers.

**Soil temperature.** In 2013, rowcover had no effect on soil temperature in the ST or PL production systems (Table 5). While minimum soil temperature was unaffected by production system in 2013, PL treatments had higher mean and maximum soil temperature both before and after rowcover removal. Before rowcover removal, mean and maximum soil temperatures were 2.1 and 3.5 °C higher in PL, respectively. After rowcover removal, mean and maximum soil temperatures were 1.0 and 2.1 °C higher in PL, respectively.

In contrast, in 2014, rowcovers increased minimum and mean soil temperature by 1.3 and 1.1 °C, respectively, before they were removed. In 2014, when averaging across rowcover treatments, PL treatments always had higher minimum, mean, and maximum soil temperatures than ST treatments; the daily minimum soil temperature was higher than ST by 1.7 to 1.8 °C, daily mean soil temperature by 1.7 to 2.0 °C, and daily maximum soil temperature by 2.0 °C. However, before the rowcovers were removed, there was no difference in soil temperature between ST with rowcover and PL without rowcover.

**Plant biomass and leaf chlorophyll content.** In both years, PL treatments had higher plant biomass than ST treatments in organically and conventionally managed fields (Table 6). Yet, in the conventionally managed field in 2014, biomass in ST with or without rowcovers did not differ from biomass in PL without rowcovers. There was no trend for the effect of production system or rowcovers on SPAD meter readings; in the conventionally managed field in 2013, however, the plants in ST without rowcovers had the highest SPAD meter readings.

**Yield.** In the organically managed field, production system affected marketable yield in both years (Table 7). Marketable yield of plants in ST was reduced by 37% and 30% compared with yield of plants in PL in 2013 and 2014, respectively. Rowcovers also affected marketable yield in both years in the organically managed field; treatments without rowcovers produced 11% and 19% fewer marketable squash compared with treatments with rowcovers in 2013 and 2014, respectively. In 2014, the marketable yield from plants in ST with rowcovers did not differ from plants in PL without rowcovers. Interaction between production system and rowcover was not statistically significant.

In the conventionally managed field, production system influenced marketable yield in both years (Table 7), as it did in the organically managed field. In 2013 and 2014, the marketable yield was reduced in ST by 21% and 17% compared with PL, respectively. In contrast to the organically managed field, rowcovers had no effect on marketable yield in either year for the conventionally managed summer squash. In 2013, plants in PL with rowcovers produced equivalent yield to ST with or without rowcovers, whereas plants in PL without rowcovers produced more squash than either ST treatment. This outcome could be explained by a windstorm that occurred just before rowcovers were removed from the squash in 2013. The wind pushed the rowcovers down onto the plants, causing many petioles to snap on the large plants in PL. Though the plants recovered, we speculate that this decreased their yield.

In 2013, there were more nonmarketable (cull) summer squash in PL treatments than in ST treatments in both the organically and conventionally managed fields. In contrast, in 2014, there was no effect of production system on number of cull summer squash in either field.

**Pesticide sprays and insect and disease incidence.** Plots with rowcovers received three fewer insecticide sprays than plots without rowcovers, as the rowcovers removed the need to spray for squash vine borer. In addition, there was often less damage to plants from squash vine borer in plots with rowcovers; this was true for organically (P < 0.0001) and conventionally (P < 0.01) managed squash in 2013, and there was marginally (P = 0.06) less damage to plants with rowcovers compared with plants without rowcovers in the organically managed field in 2014 (Table 8). All plots were sprayed twice with insecticide to control squash bug. Rowcovers did not have a strong or consistent effect on the occurrence of yellow vine decline, a disease spread by squash bug. Bacterial wilt was not observed in the plots, although cucumber beetles were present. Powdery mildew was also a problem in 2013, a drier year, and one fungicide was applied late in the season in all treatments. There were no differences in the number of pesticides applied in ST and PL plots.

**Soil MBC.** Production system had no significant effect on MBC in organically or conventionally managed plots in 2013 or 2014 (Table 9). There was, however, marginally (P = 0.056) higher MBC in the PL treatment in the conventionally managed field in 2014 than the ST treatment.

**Discussion.** Our results indicate that there is a potential for summer squash grown in a ST system to be as productive as squash grown in plasticulture. The 2013 organically managed field was the only case in which there was no equivalent yield between plants in ST and PL treatments. Walters and Kindhart (2002) found that summer squash grown in no-till and ST systems had equivalent yields compared with those grown in a conventionally tilled system, but their experiment did not involve the use of black plastic
mulch. Rowcovers increased squash yield in the ST treatments in the organically managed fields only, though we saw equivalent yields of plants in some ST and PL treatments in the conventionally managed fields as well.

We expected rowcovers to have a stronger positive effect on plant biomass production than observed, as rowcovers have been shown to increase plant biomass (Ibarra et al., 2001) and vine cover (Cline et al., 2008) in muskmelon. Nair and Ngouajio (2010) found that rowcovers increased growth of cucumber when used in a system that incorporated compost. However, because melon and cucumber have a higher optimum growing temperature compared with summer squash, it is expected that summer squash response to rowcovers would be less dramatic than that of melon and cucumber. It is also possible that the rowcovers provided too much additional heat; previous researchers have found that increasing air temperature above 40 °C can decrease plant biomass (Jenni et al., 1996) and yield (Motsenbocker and Bonanno, 1989) of muskmelon. In this study, even in treatments without rowcovers, air temperatures approached or surpassed an average daily maximum of 40 °C (Table 3), and rowcovers had a neutral or positive effect on plant biomass (Table 6) and marketable yield (Table 7). Because of their placement in the direct sun, however, air temperature sensors likely overestimated temperatures in the treatments without rowcovers. Nonetheless, our results reiterate the strong effect of PL on increased squash vegetative growth (Mahadeen, 2014).

Rowcovers had a more pronounced positive effect on squash yield in the organically managed field compared with the conventionally managed field. This could have been due to a difference in the efficacy of the pesticides used. The organic pesticides may not have been as effective as the conventional pesticides, leading to a larger discrepancy in insect damage and disease spread between rowcover and no-rowcover treatments in the organically managed fields compared with the conventionally managed fields. For example, anthracnose control was not as effective with copper as with conventional fungicides. Indeed, the incidence of squash vine borer damage and yellow vine decline tended to be higher in the organically managed plots without rowcovers than in the conventionally managed plots without rowcovers. This exemplified the advantage of rowcovers in organic management.

Though light intensity was reduced under rowcovers (Table 4), it likely did not impact the growth of plants because rowcovers were in place in June, when there were ample hours of intense sunlight. Even under rowcovers, direct sunlight should have a photon flux density beyond the saturation point for a C3 plant such as summer squash (Wells and Loy, 1985).

When averaged over rowcover treatments, plants in PL had increased yield and biomass compared with plants in ST in our study. Many researchers have measured the effect of mulch treatments on soil temperature at depths of 10 cm or less (Bonanno and Lamont, 1987; Ibarra-Jiménez et al., 2004; Schonbeck and Evanloy, 1998; Soltani et al., 1995) and found that black plastic mulch increases soil temperature compared with bare ground by 2 to 4 °C. At a depth of 9 cm, a thick layer of hay reduced afternoon soil temperature compared with bare ground by 2.5 to 4.5 °C (Schonbeck and Evanloy, 1998). Even at a depth of 15 cm, we found the soil under black plastic mulch was on average 1 to 2 °C warmer than that in ST (Table 5). In
longer, until early milk stage, can sometimes provide a more effective kill (Wayman et al., 2014). Maximal biomass production is also needed to suppress weeds effectively and retain moisture (Price and Norsworthy, 2013). Given these requirements, planting of squash is delayed, and rowcovers in a rolled rye system would likely be covering plants during the height of the summer. This could be a limitation to the ST system.

In this study, weeds were not problematic even in the ST treatments. The squash transplants grew quickly enough to shade out most weeds; in fact, no hand weeding or herbicide applications were needed to suppress weeds effectively and retain moisture in the fall as would occur with an earlier seeding date (Mirsky et al., 2009).

We hypothesized that MBC would be higher in ST treatments than in PL treatments due to the different levels of soil disruption, yet our results were inconsistent (Table 8). We chose to measure MBC specifically because it is known to be more responsive to management practices than other measurements such as soil organic carbon or soil organic matter. We also chose to take the soil samples at the end of the season to avoid the flux of microbial activity that accompanies tillage of residue into the soil; we were more interested in the baseline microbial activity after it stabilized throughout the season. However, some researchers have found no differences in MBC even after multiple consecutive years of tillage treatment differences (Awale et al., 2013; Karlen et al., 2014). Karlen et al. (2013) did find that after at least 26 years, MBC was higher in no-till plots than in those that were tilled with a moldboard plow. In addition, Overstreet and Hoyt (2008) found that after 10 years of strip tilling in the same location each year, the undisturbed region. In our study, the warm soil and organic residue-rich soil in the PL treatments could have provided a beneficial habitat for microbial growth in the short term.

We suspect that tillage treatments would need to be established for more than one growing season to see a benefit of a reduced tillage system on the baseline, or end of season, MBC. In addition, another approach called the Community Level Physiological Profiling that focuses on functional aspects related to substrate utilization by soil heterotrophic bacteria could be used to document the impact of production practices on soil microbial diversity.

The air-warming effect of rowcovers often allows growers to plant earlier in the season without risking frost damage. However, in a rolled rye system, early planting is challenging. Cereal rye should be at anthesis when using a roller crimper to kill effectively without regrowth, if not using herbicide (Mirsky et al., 2009), though waiting even

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