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Cover Crop-Based, Organic Rotational No-Till Corn and Soybean Production Systems in the Mid-Atlantic United States

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Abstract: Cover crop-based, organic rotational no-till (CCORNT) corn and soybean production is becoming a viable strategy for reducing tillage in organic annual grain systems in the mid-Atlantic, United States. This strategy relies on mechanical termination of cover crops with a roller-crimper and no-till planting corn and soybean into cover crop mulches. Here, we report on recent research that focuses on integrated approaches for crop, nutrient and pest management in CCORNT systems that consider system and regional constraints for adoption in the mid-Atlantic. Our research suggests that no-till planting soybean into roller-crimped cereal rye can produce consistent yields. However, constraints to fertility management have produced less consistent no-till corn yields. Our research shows that grass-legume mixtures can improve N-release synchrony with corn demand and also improve weed suppression. Integration of high-residue inter-row cultivation improves weed control consistency and may reduce reliance on optimizing cover crop biomass accumulation for weed suppression. System-specific strategies are needed to address volunteer cover crops in later rotational phases, which result from incomplete cover crop termination with the roller crimper. The paucity of adequate machinery for optimizing establishment of cash crops into thick residue mulch remains a major constraint on CCORNT adoption. Similarly, breeding efforts are needed to improve cover crop germplasm and develop regionally-adapted varieties.

Keywords: cereal rye; conservation tillage; cover crop; hairy vetch; high-residue cultivation; manure; nitrogen; poultry litter; sustainable agriculture; weed suppression

1. Introduction

Demand for organic grains continues to increase in the United States in response to growing consumer preference for organic feed (required for meat and milk production) and food-grade agricultural products (e.g., soymilk and tofu) [1]. Increasing societal demand for sustainable agricultural production practices likely contributes to observed increases in consumer preference for organic food [2]. Recent analysis suggests that with current premium prices, organic crop production can be highly profitable [3] even though crop yields are typically lower than in conventional systems [4]. However, production of organic grain has not kept up with demand. This has resulted in a national shortage of organic grain for direct human consumption and for livestock feed, thus requiring high levels (>60%) of imported organic grain [5]. While there are infrastructure limitations to expanding organic grain production, the inability of organic grain producers to scale up their operations due to time committed to weed and soil fertility management, as well as aversion to tillage by many conventional farmers has also contributed to the limited adoption of organic grain production. There is potential for increased domestic production of organic grains in regions that support integrated crop and livestock systems within or among farms, as organic grain production relies heavily on inexpensive supplies of organic nutrient amendments for crop production [6]. Organic production in the mid-Atlantic U.S. (encompassing the region between New York and North Carolina) has potential for expansion due to a prevalence of agricultural production systems that include small integrated crop and livestock (dairy, poultry, swine) farms, large cash-crop farms without animals, consolidated livestock operations that purchase feed grain off-farm and ready access to major metropolitan markets [7]. Annual grain production primarily occurs in the Atlantic Coastal Plain, Piedmont, and Ridge and Valley regions of the mid-Atlantic, which range from sandy to high clay content soils. Annual precipitation is relatively high (760–1012 mm) and evenly distributed, allowing for the use of cover crops in the spring or fall growing seasons.

Development of sustainable cropping systems is critical for improving soil and water conservation. In the mid-Atlantic, agriculture is currently the largest contributor of nutrient and sediment pollutants in the Chesapeake Bay watershed [8]. In response, conservation tillage (e.g., no-till) is widely promoted and incentivized in conventional grain production systems to reduce nutrient and sediment loading into the Chesapeake Bay from agricultural lands. Adoption of no-till corn and soybean production varies across the mid-Atlantic, but is estimated to range from 28%–64% of the total production area [9]. In comparison, organic corn and soybean production in the mid-Atlantic typically relies on frequent use of full-inversion tillage to incorporate nutrient amendments and crop residues, as well as to control weeds. Additional soil disturbance occurs with the use of secondary tillage for seedbed preparation and blind- or inter-row cultivation to control weeds in the cash crop. Frequent tillage and cultivation degrades soil health, increases the potential for soil erosion and is both labor and energy intensive [10,11]. Consequently, successful organic cropping systems in the mid-Atlantic rely on soil building practices, such as the integration of cover crops, the return of crop residues, use of carbon (C)-rich amendments and diversified crop rotations to mitigate the effects of frequent tillage [12]. Organic grain producers are interested in integrating conservation tillage practices with these soil building practices to increase soil quality in their production systems.

Cover crop-based, organic rotational no-till (CCORNT) corn and soybean production is one approach to integrating the soil conservation practices of no-till with the soil building practices of organic systems. CCORNT systems offer a viable alternative to tillage-based production and are being adopted by an increasing number of organic farmers [13,14]. In these systems, winter annual cover crops are mechanically terminated in the spring using a roller-crimper, and the cash crop is then no-till planted into the cover crop mulch. Labor and fuel savings are maximized when a front-mounted roller-crimper is used to terminate the cover crops, and cash crops are no-till planted in the same pass. Soybean is typically no-till planted into fall-planted cereal rye (*Secale cereale* L.) or a similar winter cereal, and corn is no-till planted into hairy vetch (*Vicia villosa* Roth) or a grass-hairy vetch mixture. Similar rolled cover crop strategies have also been developed for grain and vegetable crop systems in the southeastern [15] and the Midwestern U.S. [16]. Central features common to rolled cover crop strategies include reliance on roll-crimped cover crop mulches (grasses and legumes) as the primary mechanism of within-season weed suppression and the contribution of nitrogen (N)-fixing legume cover crops to meet the high N-demand of the subsequent cash crop (e.g., corn). Optimizing cover crop biomass accumulation to enhance physical suppression of weeds is critical to the success of no-till cash crop production. Consequently, practices that improve cover crop performance (e.g., tillage for cover crop seedbed preparation, early seeding and high seeding rates) are typically employed. Simulation models indicate that a rotational no-till approach has the potential to increase C sequestration, reduce greenhouse gas emissions and increase energy efficiency via reduced diesel fuel and labor needs in comparison to current tillage-based organic annual grain systems that rely on primary tillage before both cover and cash crops [13].

Improved crop, nutrient and pest management strategies are needed to develop CCORNT grain production systems in the mid-Atlantic that successfully meet production and conservation goals. Soil and climate influence the feasibility and performance of various integrated, multi-tactic approaches. In the mid-Atlantic, CCORNT corn and soybean research has primarily focused on developing general principles for optimizing cover crop performance and management, devising multi-tactic weed management strategies and improving cash crop planter configurations [13,14]. The aim of this paper is to update past reviews [13,14] by collating recent and ongoing research that addresses the constraints that limit producer adoption and the practices that improve the performance of both cover and cash crops. First, we present an overview of the production viability of CCORNT in the mid-Atlantic, by comparing the yield output and yield stability of these systems against county-level averages and tillage-based organic production systems. We then evaluate cover crop practices and integrated, multi-tactic pest management strategies, focusing our discussion on the two dominant regional grain crops: corn and soybean. Lastly, we identify major constraints and research priorities needed to further improve the potential of CCORNT in the mid-Atlantic U.S.

2. Corn and Soybean Yield Performance in CCORNT

The viability of CCORNT production systems hinges on the development of integrated cover crop, nutrient and pest management strategies that result in consistent high yielding cash crops across a range of soil and environmental conditions. Recent research has evaluated a suite of cover crop and weed management approaches during the organic transition period within a winter wheat (*Triticum aestivum*)-hairy vetch/triticale (*x Triticosecale* Wittm.)-no-till corn-cereal rye-no-till soybean rotation. The research project, known as the Reduced-tillage Organic Systems Experiment (ROSE), was an inter-disciplinary, multi-institutional effort between 2010 and 2013 at Pennsylvania State University, the USDA Agricultural Research Service (ARS), Sustainable Agricultural Systems Laboratory at Beltsville, Maryland, and the University of Delaware (Supplemental Table S1). The ROSE tested the role of cover crop termination date (early, intermediate and late) and high-residue cultivation (+/−) in the no-till corn and soybean phases of the rotation. These treatments were imposed in a full-entry cropping system experimental design. This enabled the evaluation of how cover crop and pest management approaches influenced cash crop performance and pest management objectives within-season and across the three-year rotation. Delayed cover crop termination has the potential to improve cash crop management via higher levels of weed suppression and N provisioning services that result from higher levels of cover crop biomass accumulation. However, this strategy can constrain cash crop growing season length. In the ROSE, shorter season crop varieties were used when cover crop termination was delayed for both corn and soybean systems (Table 1).

Table 1. Cereal rye biomass and soybean yields in an organic cover crop-based rotational no-till experiment (2011–2013) conducted by Penn State University, the USDA Agricultural Research Service (ARS) Sustainable Agricultural Systems Laboratory in Beltsville, MD and University of Delaware. Cereal rye biomass and soybean yields are averaged across high-residue cultivation treatments (n = 2), blocks (n = 4) and years (n = 3; 2011–2013) for the three planting date treatments (early, middle, late) evaluated in the experiment. The coefficient of variation (CV) is reported to describe inter-annual yield variability (2011–2013) among alternative planting date strategies and county-level average conventional yields.

Site (Soybean Production)	Planting Date (Maturity Group) †	Planting Date Range (2011–2013)	Cereal Rye Biomass Mean (CV%)		Soybean Yield Mean (CV%)	
			Mg ha^{-1}			
Penn State University Rock Springs, PA	Early (2.9)	26–31 May	5.3	(21)	3.2	(5)
	Middle (2.7)	3–6 June	5.8	(16)	3.3	(5)
	Late (1.1)	11–17 June	7.0	(20)	2.7	(11)
	County Average Yield		—		*3.2*	*(6)*
USDA-Beltsville Beltsville, MD	Early (3.8/4.3)	3–28 May	6.4	(29)	3.3	(27)
	Middle (3.4)	11 May–5 June	7.4	(31)	3.8	(22)
	Late (2.7)	18 May–17 June	8.2	(33)	3.4	(39)
	County Average Yield		—		*2.7*	*(10)*
University of Delaware Georgetown, DE	Early (3.8/4.3)	3–21 May	7.7	(15)	1.7	(16)
	Middle (3.4)	8–28 May	8.6	(6)	2.6	(1)
	Late (2.7)	15 May–5 June	9.9	(11)	1.9	(16)
	County Average Yield		—		*2.7*	*(7)*

† Maturity groups are based on ~150 km latitudinal gradients from south (4 s) to north (1 s) in the mid-Atlantic region.

Delayed cover crop termination in CCORNT soybean systems resulted in greater cereal rye biomass across mid-Atlantic locations, with step-wise increases in biomass levels observed across planting dates at more southern (Maryland and Delaware) locations (Table 1). However, cereal rye biomass is only one of several interacting factors that can influence soybean yields in CCORNT systems. For example, lower soybean yields were observed when planting dates were delayed until mid-June at the Pennsylvania location, which can be attributed in part to the shorter growing season in the northern mid-Atlantic. In comparison, later planting dates at the southern locations produced soybean yields comparable to early planting dates. At each mid-Atlantic location, the highest yielding planting dates were comparable to county-level averages for conventional soybean production (Table 1). Moreover, inter-annual yield variability was also comparable to county averages.

Delayed cover crop termination in no-till corn systems produced similar regional trends to soybean (Table 2). In general, hairy vetch/triticale biomass increased as cover crop termination was delayed, but observed trends suggest that corn yields were not positively correlated with cover crop performance. In more northern areas of the mid-Atlantic (Pennsylvania), the relatively short growing season required corn to be harvested for silage to enable primary tillage, seedbed preparation and cereal rye establishment prior to no-till soybean production. Earlier planting dates resulted in higher corn silage yields at the Pennsylvania location, but yields were consistently below (16%–34%) county-level averages for conventional corn silage production over the same period. Longer fall growing seasons in southern areas of the mid-Atlantic (Maryland and Delaware) enabled cereal rye establishment following corn grain production. In the ROSE, corn grain yields were well below county averages in Delaware, but exceeded county averages in Maryland. Despite variations in yield, organic rotational no-till production of both corn and soybean was profitable without the need to factor in organic price premiums at the Pennsylvania and Maryland locations each year and in one year at Delaware [17].

Table 2. Cover crop (hairy vetch/triticale) biomass and corn yields in an organic cover crop-based rotational no-till experiment (2011–2013) conducted by Pennsylvania State University (Rock Springs, PA), USDA Agricultural Research Service (ARS; Beltsville, MD, USA) and University of Delaware (Georgetown, DE, USA). Cover crop biomass and corn yields are averaged across treatments (n = 2; +/− high-residue cultivation), blocks (n = 4) and years (n = 3; 2011–2013) for the three planting date treatments (early, middle, late) evaluated in the experiment. The coefficient of variation (CV) is reported to describe inter-annual yield variability (2011–2013) among alternative planting date strategies and county-level average conventional yields.

Site (Corn Grain/Silage)	Planting Date (Hybrid Maturity)	Planting Date Range (2011–2013)	Cover Crop Biomass Mean (CV%)		Corn Yield Mean (CV%)	
			Mg ha^{-1}			
Penn State University	Early (99 day)	31 May–1 June	5.9	(8)	35.8	(10)
Rock Springs, PA	Middle (95 day)	7–12 June	6.4	(2)	31.2	(2)
(silage)	Late (85 day)	15–18 June	6.4	(1)	28.0	(14)
	County Average Yield		—		42.2	*(26)*
USDA-ARS	Early (104 day)	13 May–4 June	5.6	(17)	7.5	(8)
Beltsville, MD	Middle (99 day)	24 May–12 June	5.8	(3)	7.0	(31)
(grain)	Late (88 day)	31 May–18 June	6.0	(15)	7.6	(13)
	County Average Yield		—		6.0	*(48)*
University of Delaware	Early (104 day)	4–30 May	5.5	(27)	3.8	(35)
Georgetown, DE	Middle (99 day)	11 May–6 June	6.4	(12)	5.2	(9)
(grain)	Late (88 day)	16 May–17 June	7.2	(6)	3.6	(14)
	County Average Yield		—		9.3	*(11)*

Compared with mid-Atlantic county-level averages, soybean yields in the ROSE were generally more consistent than corn yields. This difference in yield stability between corn and soybean has been observed in previous studies of CCORNT systems [13]. Inconsistent organic no-till corn performance in the mid-Atlantic could be due, in part, to regional constraints on fertility management. Southern areas of the mid-Atlantic have access to poultry litter for corn crop production. Pelletized poultry litter was broadcast at planting in Delaware and subsurface-banded at side-dress using custom-fabricated banding equipment at the Maryland location. In comparison, the Pennsylvania location utilized liquid dairy manure and applied it during the late-summer hairy vetch establishment phase the previous summer, approximately nine months prior to corn establishment. The effect of these different fertility practices likely influences N availability to corn during corn peak N demand. Further research is needed to determine if asynchrony between corn peak N demand and N supply from fall-applied liquid dairy manure is a significant constraint that may limit adoption of CCORNT corn production in dairy-based regions of the mid-Atlantic.

Beyond comparisons with county-level averages, which are predominantly based on yield data for conventionally-managed farms, it is critical to compare the yield performance of organic rotational no-till against tillage-based organic systems, in order for traditional tillage-based organic grain farmers to determine the value of CCORNT. Experiments comparing CCORNT against tillage-based organic systems have been conducted at the Agricultural Research Center in Beltsville, Maryland since 2008 (Supplemental Table S1). Data collection has primarily focused on corn (2008–2016 growing seasons), but new data are now emerging for soybean (2015–2016 growing seasons). These data show no difference in soybean grain yields between CCORNT and tillage-based systems, while corn grain yields in CCORNT increased compared with tillage-based systems (Figure 1). These results suggest that, despite the greater operational challenges associated with CCORNT, there is an opportunity to increase yield output in these organic systems. However, maintaining consistent corn yields across years in CCORNT systems remains a major challenge. Planting through thick mulch can interfere with achieving satisfactory seed-soil contact, which can result in inconsistent establishment of targeted corn populations and low yields. Soybean can recover from inconsistent germination and establishment due to having a comparatively higher seeding rate [18]. In addition, the later planting dates required in more northern parts of the mid-Atlantic (due to climate conditions) can further negatively impact CCORNT corn yields.

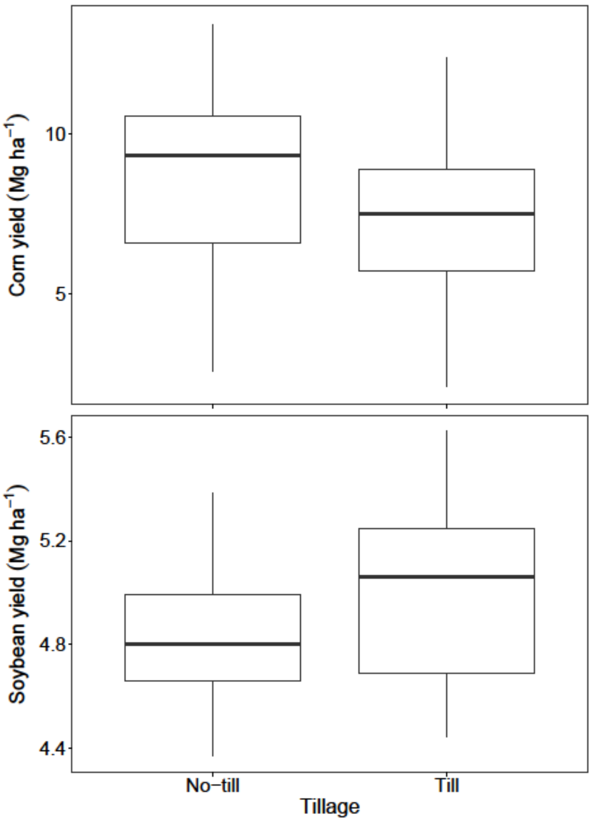

Figure 1. Corn and soybean grain yields in organic rotational no-till systems (No-till) and tillage-based organic systems (Till) at the Agricultural Research Center, Beltsville, Maryland. Corn data span the 2008–2016 growing seasons (2008–2010 with monoculture hairy vetch cover crop; 2011–2016 with cereal rye/hairy vetch cover crop mixtures); soybean data are from the 2015–2016 growing seasons. Corn yields were significantly greater in no-till compared with till ($F_{1,50}$ = 6.45, p = 0.01); soybean yields did not differ between systems. Box plots represent the median (horizontal line), interquartile range (box) and the maximum and minimum values (end of each vertical line).

3. Cover and Cash Crop Management in CCORNT

Management strategies that produce high cover crop biomass and optimal cash crop yields are critical to the success of CCORNT corn and soybean production. Critical challenges of CCORNT systems include: (1) poor cover crop establishment, which can negatively impact biomass accumulation and subsequent weed suppression; (2) poor establishment of legume cover crops, which reduces N-fixation; (3) failure to adequately terminate the cover crop, which negatively affects cash crops via light, water and nutrient competition; and (4) planter configurations that cannot sufficiently cut through or remove cover crop biomass, which can lower cash crop populations and yields. Consequently, understanding the potential agronomic tradeoffs related to cover and cash crop management strategies is critical for improving the consistency of CCORNT soybean and corn systems.

3.1. Soybean

Agronomic factors influencing the success of no-till planting soybean into roller-crimped cereal rye in the mid-Atlantic have been well documented [19,20]. In our experience, CCORNT soybean systems have produced competitive yields more consistently than corn. This can be attributed in part to the fact that soybeans have less management complexity than corn. The cereal rye monocultures used prior to soybean are typically easier to manage than legume-grass mixtures utilized prior to corn. Here, we discuss best management practices for optimizing cereal rye biomass accumulation and subsequent termination with a roller crimper, alternative winter grains for no-till soybean systems and multi-tactic strategies that improve weed management.

3.1.1. Cover Crop Establishment Prior to Soybean

Previous research has identified agronomic practices that improve cereal rye establishment and performance in no-till soybean systems [14]. These practices include manipulating establishment timing, seeding rates and soil fertility to maximize cereal rye biomass production and ground cover [21,22]. Soybean typically follows corn in rotation in the mid-Atlantic. In the northern mid-Atlantic (e.g., Pennsylvania and New York), late-fall corn grain harvest limits the agronomic window for cereal rye establishment, but a longer fall growing season in southern mid-Atlantic states (e.g., Maryland and North Carolina) allows for consistent cereal rye establishment. In our experience, adequate seedbed preparation is critical to maximizing cereal rye performance. Prioritizing earlier corn harvest to ensure sufficient time for corn stover management and primary and secondary tillage is often necessary. Based on the window of time afforded by the previous crop, producers can either prepare a seedbed with tillage prior to drilling or no-till drill cover crops. Processing previous corn stover residues with a turbo-till often suffices to ensure optimal cover crop establishment. Historically, we have advocated tillage prior seeding fall cover crops, as perennial weeds and pest cycles are most effectively controlled with primary tillage using a chisel- or moldboard-plow. However, during wet falls, it may be best to avoid tillage and no-till plant cover crops, as seeding into tilled ground can be greatly stalled by a wet fall. However, research and experience have repeatedly demonstrated that cover crop establishment and growth are greater with a prepared seedbed.

Based on our body of research, best management practices for cereal rye establishment include seeding at high rates (approximately 134 kg ha^{-1}) with a grain drill. Increasing cereal rye seeding rates has been shown to increase weed suppression due to greater ground cover in early spring [22]. The use of a grain drill improves establishment and provides a more uniform plant population in comparison to broadcast methods. Alternative practices that have been employed include a dual seeding method in which seed is both drilled and broadcast to encourage increased ground cover in inter-row spaces. Finally, while cereal rye is an efficient scavenger of residual inorganic soil N, it may also be necessary to fertilize cereal rye to maximize biomass and ground cover when soil mineralizable N levels are low.

3.1.2. Cover Crop Termination Prior to Soybean

Optimizations of cover crop termination efficacy and biomass accumulation are the primary factors that influence cover crop termination timing decision-making. Mechanical control of cereal rye using a roller-crimper is most effective when terminating after anthesis, with >85% control of cereal rye occurring once the Zadoks growth Stages 60–65 are reached [21]. Cover crop mulches suppress weed germination and growth of summer annual weeds via physical obstruction and by lowering light and temperature at the soil surface [14]. The level of cover crop biomass typically needed to provide high levels of weed suppression (>8000 kg ha^{-1}) requires delayed cash crop planting and good base soil fertility [23,24]. Delaying cover crop termination by only 7–14 days can result in significant gains to cover crop biomass accumulation. In the mid-Atlantic region, cereal rye biomass accumulation can increase 200 kg ha^{-1} day^{-1} after stem elongation [21]. Consequently, delayed cereal rye termination is a viable strategy for increasing the weed suppression potential of surface mulch residue. Other cultural strategies that can be integrated with delayed cereal rye termination to maximize weed suppression include earlier fall planting [21] and increased seeding rates to enhance cereal rye ground cover in early spring [22].

Cover crop termination timing can also shift the composition of weed species in CCORNT systems by altering both cover crop biomass accumulation (increasing with delayed termination) and the timing of mechanical control in relationship to weed emergence. For example, in a Pennsylvania experiment, insufficient canopy cover from cereal rye resulted in the emergence of common ragweed (*Ambrosia artemisiifolia* L.) prior to cover crop termination with the roller crimper, which did not control emerged common ragweed seedlings [19]. In comparison, later emerging summer annual species such as giant foxtail (*Setaria faberi* Herrm.) and smooth pigweed (*Amaranthus hybridus* L.) were less abundant. The selection of dominant weed flora was associated with germination prior to rolling and survival following the rolling operation.

The ROSE demonstrated that volunteer cover crops have the potential to limit the viability of CCORNT practices in annual grain rotations [25]. Although previous studies have identified the optimal termination timing for limiting regrowth of roller-crimped cover crops, most research has been conducted using annual experiments that did not track management legacy. Consequently, the agronomic impacts of volunteer cover crop recruitment that may result from cover crop seed production following even low levels of regrowth are not well understood. In the ROSE, within-season control of cereal rye with the roller-crimper improved as termination was delayed, but cereal rye continued to mature on the ground when termination occurred after the onset of the milk stage (>Zadoks 70). Regardless of cover crop termination timing, volunteer cereal rye was detectable across locations in winter wheat (Figure 2); in some cases, grain contamination levels approached the 5% maximum threshold allowed for foreign materials in food-grade wheat. Consequently, there is likely a narrow agronomic window from 50% anthesis (Zadoks 65) to the milk stage (Zadoks 70–79) for optimizing cereal rye control and minimizing the effect of volunteer cover crops in subsequent years. System-specific strategies are needed to manage volunteer cover crops in CCORNT systems. For example, the ROSE revealed that a comparatively longer fall growing season in Delaware allowed for false seed-bedding before winter wheat, which minimized volunteer cereal rye issues. Alternatively, following the soybean phase of the rotation with a spring- or summer-sown crop provides an opportunity to manage volunteer winter cover crops with tillage prior to planting the next crop in rotation. Other strategies may include multiple roller passes or more aggressive roller-crimper technology.

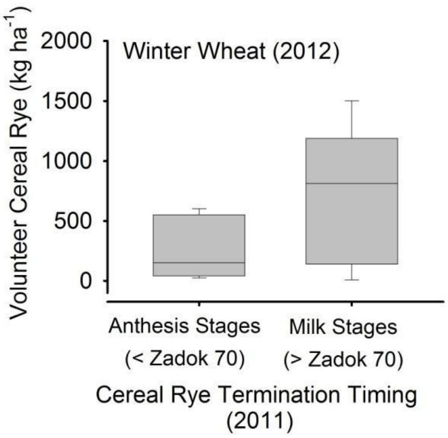

Figure 2. Effect of cereal rye termination timing in 2011 on volunteer cereal rye abundance in the following winter wheat cash crop (2012) at the Pennsylvania and Maryland locations (data from the Reduced-tillage Organic Systems Experiment (ROSE)). Cereal rye termination ranged from the onset of anthesis (Zadoks 59) to the soft dough stage (Zadoks 85).

Although cereal rye is the most commonly-used cover crop species in CCORNT soybean production, other winter cereal species might provide advantages over cereal rye. As the timing of cover crop termination is based on cover crop phenology, using an earlier-maturing species such as barley (*Hordeum vulgare* L.) might enable earlier termination and soybean planting and, thus, a longer soybean growing season and greater yield potential. In an experiment conducted in Maryland and New York from 2013–2014 (Supplemental Table S1), delaying termination by one week resulted in greater biomass for both cereal rye and six-row barley (Figure 3A). For each species at each site, terminating the cover crop later reduced both weed biomass (Figure 3B) and the percentage of uncontrolled cover crop plants, or "bounce-back" (i.e., plants that survived rolling-crimping and returned to their upright growth habit). In Maryland, cover crop bounce-back decreased from 5% down to 0% for barley and 3% down to 0% for cereal rye as termination timing was delayed by one week. In New York, the later termination time reduced cover crop bounce-back from 17% down to 11% for barley and 9% down to 6% for cereal rye. Although termination efficacy tends to be proportional to cover crop growth stage, we did not observe less bounce-back with barley compared to cereal rye, despite barley maturing earlier in the spring. Interestingly, we also did not observe increased weed suppression in cereal rye despite greater cover crop biomass production than barley. Soybean yield was similar across all combinations of species and termination times at each site (Figure 3C), suggesting that competition between uncontrolled cover crops and soybean was negligible. Results from this experiment indicate that lower levels of cover crop biomass (5000–6000 kg ha^{-1}) can provide adequate weed suppression in the northern mid-Atlantic, which might help alleviate some of the challenges associated with soybean seed placement through thick layers of mulch. Our results also suggest that barley might be able to compensate for lower biomass production and achieve relatively high levels of weed suppression due to a more rapid canopy closure and wider leaf blades compared to cereal rye [26].

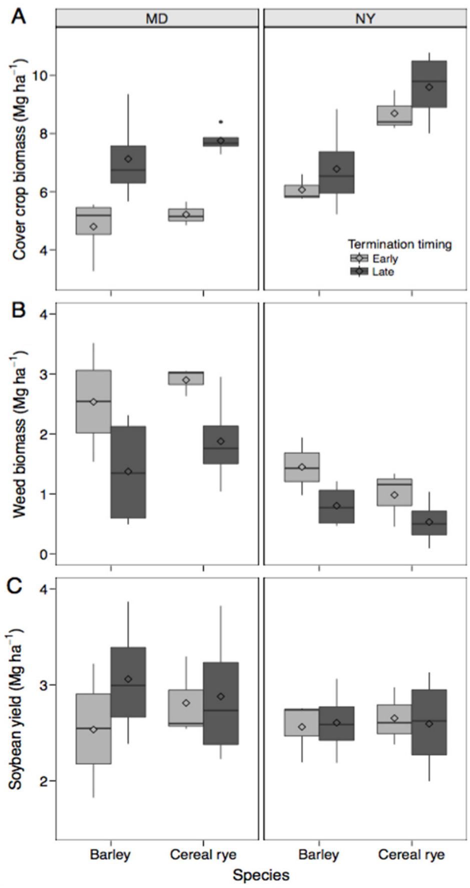

Figure 3. The impact of cover crop termination timing on cover crop biomass (**A**), weed biomass (**B**) and soybean grain yield (**C**) using six-row winter barley and cereal rye cover crops in Maryland (MD) and New York (NY) in 2014. Late termination timing occurred one week after the early date. Box plots represent the mean (open diamond symbol), median (horizontal line), interquartile range (box) and the maximum and minimum values (end of each vertical line). For each response, species and termination timing were included as fixed effects: cover crop biomass ($F_{1,25}$ = 12.68, p = 0.0015 for species and $F_{1,25}$ = 12.33, p = 0.0017 for termination timing); weed biomass ($F_{1,25}$ = 0.032, p = 0.86 for species and $F_{1,25}$ = 11.65, p = 0.0022 for termination timing); and soybean yield ($F_{1,20}$ = 0.0041, p = 0.95 for species and $F_{1,20}$ = 0.90, p = 0.35 for termination timing).

3.1.3. Soybean Planting and Management

In contrast to conventional and tillage-based organic soybean production, farmers that manage soybean in CCORNT systems must overcome the unique challenges associated with planting through thick cover crop mulch. In particular, achieving adequate soybean seed-to-soil contact can be difficult [27]. Soil moisture can be depleted through cover crop transpiration, thereby inhibiting soybean germination [27–29], and soybean lodging can be problematic as hypocotyl elongation may weaken stem strength [30].

It is recommended to plant soybean in the same direction as roller-crimping (ideally in a single pass) so that the coulters on a no-till planter can part the residue rather than be forced to cut through cover crops rolled perpendicularly to the direction of planting. However, cover crop residue can still be pushed into the seed furrow (i.e., hair-pinning), which can impede seed-to-soil contact [31,32]. In such instances, it is common to observe desiccated, non-germinated soybean seed on top of the hair-pinned residue, especially when the soil is dry and the closing wheels are unable to cover the furrow. Row cleaners (trash wheels) can reduce hair-pinning by moving cover crop mulch away from the soybean row [29]. There are several commercially-available trash wheels, but units must have a narrow blade angle and ideally overlap in order to adequately both cut and move trash. We have customized planters to include an extra toolbar in front of the double-disk opener and unit mounted coulter. This extra toolbar has residue slicers put in line with the unit mounted coulters. The residue slicers have depth wheels on each side of the coulter, which help press residue down and improve the cutting action. The frame mounted residue slicers provide additional cutting action. Trash wheels have also been mounted to the frame and thereby provide two sets of coulter and trash wheels to adequately move residue and cut the remaining material prior to planting. This can improve soybean seed placement and germination, but in some cases, the residue can become wrapped around the row cleaners, impairing their function [13]. Moreover, mulch covering the crop row is important for in-row weed suppression. If row cleaners move too much residue, emerging crop seedlings can suffer from increased weed competition. Many of these machinery considerations also apply to CCORNT corn.

Using higher soybean planting rates is an effective cultural weed management practice [20,33–35]. Higher soybean planting rates enhance weed-crop competition primarily through earlier crop canopy closure and greater shading [33,36,37]. High planting rates can also help maintain maximum yields [34,38]. The price premium for organic soybean (five-year average for feed-grade soybean = \$0.92 kg^{-1} [39]) helps ensure that high planting rates are profitable for organic farmers despite the increase in seed cost. Narrower row spacing (<76 cm) can also be used to hasten canopy closure, but this precludes the option of high-residue, inter-row cultivation to manage inter-row weeds.

Multi-tactic approaches that combine cultural strategies for maximizing cover crop biomass with supplemental high-residue, inter-row cultivation have been investigated [26,40,41]. High-residue cultivators for no-till soybean and corn systems typically have two depth-gauge wheels with a residue-slicing coulter between the wheels, which are followed by a single wide flat sweep. The sweep cuts through the soil at a 2.5–5-cm depth, slicing the root systems of weeds while leaving the surface residue mostly intact. Unlike most inter-row cultivators that are most effective on small weed seedlings before their root systems become established, high-residue cultivators are more effective on weeds after they have become established. Standard cultivators rely on dislodging these small seedlings, while the high-residue cultivator's sweeps separate the roots from the above-ground portion of the plant. Nord et al. [41] found that cereal rye biomass alone provided high levels of weed suppression when weed infestations were low, but high-residue cultivation was needed to achieve acceptable levels of weed suppression when weed infestations were high (i.e., supplemented weed seedbank), regardless of cereal rye biomass accumulation. High-residue cultivation can effectively control summer annual weeds that emerge prior to cover crop termination, such as common ragweed [26,41]. The Rodale Institute (PA) tested the effects of high-residue cultivator timing on weeds in rotational no-till soybeans at 3–4, 5–6 and 7–8 weeks after soybean planting [42]. Averaged across timings, high-residue cultivation resulted in a 67% reduction in weed biomass compared to the no-cultivation control, and soybean yields were 12%–22% higher in high-residue cultivation treatments compared to the control.

The ROSE investigated the use of high-residue inter-row cultivation and delayed cover crop termination as a multi-tactic weed management approach. Delaying cereal rye termination by 7–14 days to increase surface residue mulch produced variable results as a weed management strategy. Total cover crop biomass accumulation and biomass gain with delayed termination varied by location and year (Table 1). Regional differences in weed species response to delays in cover crop termination were also observed, similar to that found by Nord et al. [19] and Teasdale and Mirsky [43]. In comparison, high-residue, inter-row cultivation consistently lowered summer annual weed biomass across various termination timings and study locations in no-till corn and soybean systems (Figure 4). Summer annual weed biomass was also consistently low in the winter wheat phase of the rotation (<100 kg ha^{-1}), regardless of weed biomass levels in no-till soybean across different planting dates. Our experience in the mid-Atlantic suggests that high-residue cultivation will be a necessary tool to prevent exponential increases in weed seedbanks during years when poor cover crop performance or other agronomic factors lead to higher weed infestation levels. Furthermore, mulches have a minimal effect on perennial weeds, which become more challenging in CCORNT systems. High-residue cultivation can serve as an important tool to manage perennial weeds in CCORNT soybean and corn systems [13,14].

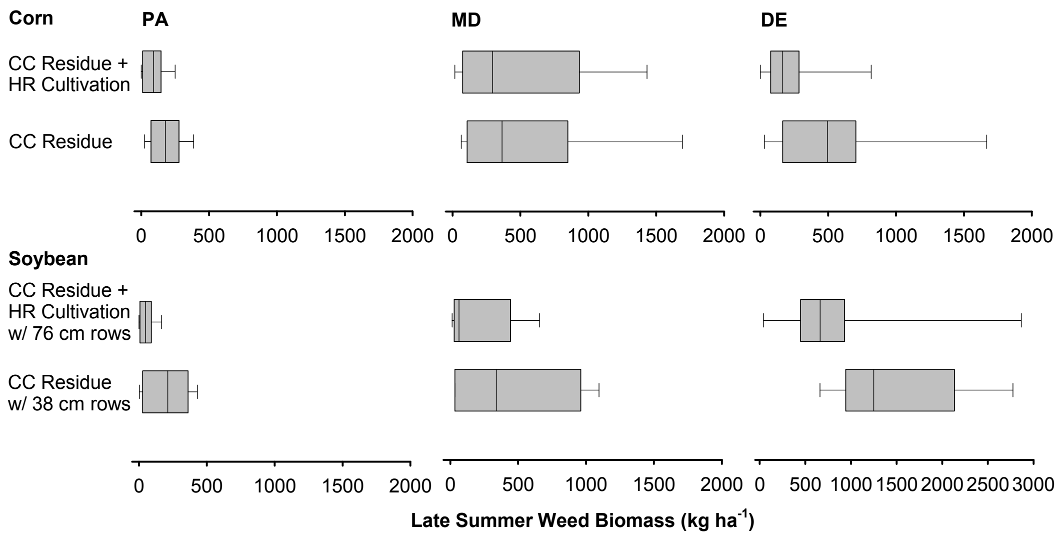

Figure 4. Effect of rolled cover crop (CC) surface residue on weed biomass with or without the use of high-residue (HR) inter-row cultivation; data from the Reduced-tillage Organic Systems Experiment (ROSE). In Pennsylvania (PA), HR cultivation in no-till corn decreased weed abundance ($F_{1,55}$ = 8.1, p = 0.006). In Delaware (DE, $F_{1,55}$ = 13.7, p < 0.001) and Maryland (MD, $F_{1,55}$ = 3.7, p = 0.05), HR cultivation in no-till soybean decreased weed abundance compared to when soybean was planted on 38-cm rows in the absence of HR cultivation, which was evaluated as an alternative weed control strategy.

3.2. Corn

Tillage-based organic corn production has typically out-performed tillage-based organic soybean production, likely because corn rapidly canopies and is therefore more competitive against weeds [44]. In organic no-till systems, however, corn production involves greater management complexity compared to soybean production due to higher N demand. Legume-based cover crops do not typically provide sufficient N in no-till corn, and supplemental organic sources are required. Organic nutrient sources are more difficult to apply than inorganic sources and are also more tightly regulated in the Chesapeake Bay watershed (e.g., Maryland mandates incorporation or subsurface banding of poultry litter). While cover crops in the soybean phase must be managed primarily to control weeds, cover crops in the corn phase must be managed to control weeds and provide a source of N. This necessitates the use of cover crop mixtures prior to corn, for which selection and management is more complex. Below, we review corn production management intricacies and constraints.

3.2.1. Cover Crop Establishment Prior to Corn

In the mid-Atlantic region, organic corn is typically planted after a wheat or soybean grain crop. The timing of summer grain harvest dictates the time allowed for legume cover crop establishment. Legume cover crops require earlier planting dates than grasses to produce acceptable levels of biomass and to survive the winter, particularly in the northern mid-Atlantic [24,45]. Initial organic no-till research focused on preceding corn with a hairy vetch monoculture [45]. Hairy vetch is a winter-hardy legume with rapid growth that produces large amounts of biomass, has an optimal suite of characteristics for adding considerable N to the system, and provides some weed control [45]. However, more recent research has switched focus to mixtures of hairy vetch and winter grains, as hairy vetch alone was found to not provide sufficient weed control.

Hairy vetch monocultures or winter grain/hairy vetch mixtures are best established using a grain drill. These species mix well in seed hoppers with minimal separation, resulting in optimal cover crop stands. The proportion of each species in the mixture should be chosen carefully to balance tradeoffs in managing both nitrogen and weed suppression. For example, a recent mid-Atlantic study demonstrated that a wide range of hairy vetch/cereal rye mixture proportions produced >8 Mg ha^{-1}, which is considered to be the biomass threshold for acceptable levels of weed suppression in the southern mid-Atlantic, but a hairy vetch/cereal rye seeding rate of 27/34 kg ha^{-1} was needed to achieve maximum N content and low C:N ratios [46]. Selection of mixture seeding rates should also consider initial field conditions. Sites with low residual soil fertility will favor the growth of the legume(s) in a mix due to the ability of legumes to fix atmospheric N, whereas grasses in a mix are likely to dominate on high fertility sites due to their rapid growth and ability to scavenge N [47]. Seeding rates should be adjusted according to the primary needs of the site (e.g., N-fixation, weed control, etc.) to take advantage of site conditions, minimize seed costs, and maximize the benefits provided by the cover crops.

3.2.2. Cover Crop Termination and Corn Planting

Cereal rye and hairy vetch are terminated most effectively when roller-crimped at anthesis. However, asynchrony between cereal rye and hairy vetch anthesis presents a termination challenge. Hairy vetch is best controlled through the combined action of a roller-crimper (which initially damages the cover crop) and a cash crop planter (which aids termination by adding additional wheel traffic and cutting the cover crop). Research has thus focused on a range of termination strategies to optimize the control of the cover crop mixture using a roller alone and in combination with a planter. We have rolled immediately before planting (roll/planted), rolled twice before planting (roll-roll/planted) and rolled, planted and rolled again before crop emergence (roll/planted-roll). We have found that hairy vetch is not completely killed by rollers alone and that a second rolling three to ten days later (roll/plant-roll), depending on site conditions, provides an opportunity to kill any cover crops not terminated with the first pass. This approach is also better than the roll-roll/plant approach, as a rain event between the first rolling and second can greatly delay planting since a terminated cover crop mulch does not transpire and lowers evaporation.

Corn planting date is strongly affected by timing of cover crop termination, and performance has been noted to decline in more northern regions when the later flowering of hairy vetch delays planting [13,48]. In this case, lower corn yields are due to decreased growing degree days (GDD, i.e., a shorter growing season). Recent research in Maryland and North Carolina has found that planting corn when hairy vetch reaches 50% flowering had little to no negative effect on corn yields as compared with earlier corn planting dates [49,50]. These results may reflect the greater flexibility of CCORNT corn production in more southern regions of the mid-Atlantic compared with more northern regions, due to their longer growing season. Matching corn cultivar maturity groups with local climate (i.e., typical patterns of GDD accumulation) can better accommodate shorter growing seasons in the north.

3.2.3. Cover Crops and Weed Control in Corn

Cover crop termination method and timing also have important implications for weed management in no-till corn systems [43]. In a Pennsylvania experiment, perennial weed species were found to be less suppressed by hairy vetch cover crop residues than annual weed species [51], and full-season weed suppression via cover crop residues can be inconsistent [19,21,41]. Consequently, inter-row high-residue cultivation is often needed to provide greater weed suppression. For example, high-residue cultivation in corn planted after a hairy vetch monoculture improved weed control, relative to no cultivation, by 23%–78% over a three-year study [49]. Optimization of the timing and frequency of high-residue cultivation will be critical for designing multi-tactic strategies that result in consistent levels of weed control. A recent Pennsylvania study suggests that two high-residue, inter-row cultivation passes at approximately four and six weeks after planting are needed to provide consistent levels of weed control in reduced-tillage corn with or without cover crop surface mulch residue [40]. This strategy allows for killing both early emerging or fast growing species and later emerging species that were too small to be susceptible in the first pass. However, in addition to increased fuel and labor costs, additional cultivation passes result in less persistent cover crop residue, particularly in the case of more readily-decomposable hairy vetch cover crops. Though not yet documented for high-residue cultivation, disturbance to the legume mulch and soil, and the resulting increase in soil-cover crop contact, has also been shown to increase rates of N availability in the soil [52].

In comparison to legume monocultures, legume/grass cover crop mixtures may also improve weed control and are therefore recommended as the preferred cover crop for corn production. Hairy vetch alone can stimulate weed germination and growth and is an unreliable tool for weed control [51]. In a two-year experiment conducted by USDA-ARS at the Beltsville Agricultural Research Center in Beltsville, Maryland (Supplemental Table S1), hairy vetch monocultures significantly increased weed biomass as compared to cereal rye/hairy vetch mixtures (Figure 5). Strikingly, cover crop mixtures containing only 20% cereal rye and 80% hairy vetch produced the same reductions in weed biomass relative to a hairy vetch monoculture (approximately 70%) as a cereal rye monoculture (Figure 5). We speculate that cereal rye provides structural support for hairy vetch, minimizing plant tissue contact with the soil surface. The soil surface is noticeably wetter and warmer under hairy vetch monocultures, and its prostrate growth habit results in rapid decomposition even while the plant is still growing [53]. Since N is known to stimulate both weed germination and growth [54], grass/legume mixtures that delay N release allow producers to address both weed and N management needs. However, as we discuss in greater detail below, grass/legume mixtures decrease the overall N available for a corn crop when compared to a pure legume cover crop and, thus, may require supplemental sources of N.

Failure to effectively terminate cereal rye and hairy vetch can lead to non-terminated cover crops reaching maturity, which may result in competition with the corn crop for resources during early growth and development and in seedbanks that result in volunteer cover crops in future seasons [51]. Hairy vetch produces hard seed that can easily become a volunteer weed problem [25,55]. In our experience, hairy vetch termination needs to be delayed until flowering to achieve high levels of control, but viable seed production occurs very soon after flowering. In the ROSE, the control of hairy vetch with a roller-crimper improved as termination was delayed, but mature seeds were produced for both cover crops (cereal rye and hairy vetch) and emerged as volunteers within the cereal rye-no-till soybean and winter wheat phases of the rotation regardless of termination timing (Figure 6). Volunteer hairy vetch contamination in winter wheat was negligible (<1%) following the three termination timings at the Pennsylvania location, but impacted wheat yields (10%–29%) at the Maryland location. Furthermore, volunteer hairy vetch plants increased in the cereal rye-no-till soybean phase because optimal timing for cereal rye termination with the roller-crimper occurs when hairy vetch is still vegetative and is thus poorly controlled by the roller-crimper pass. Observational evidence suggests that two roller-crimper passes spaced approximately 5–8 days apart can improve the control of hairy vetch/triticale mixtures and thus reduce volunteer hairy vetch populations. Additional labor and fuel costs associated with this extra pass may be warranted to minimize volunteer cover crops in subsequent crop phases of the rotation.

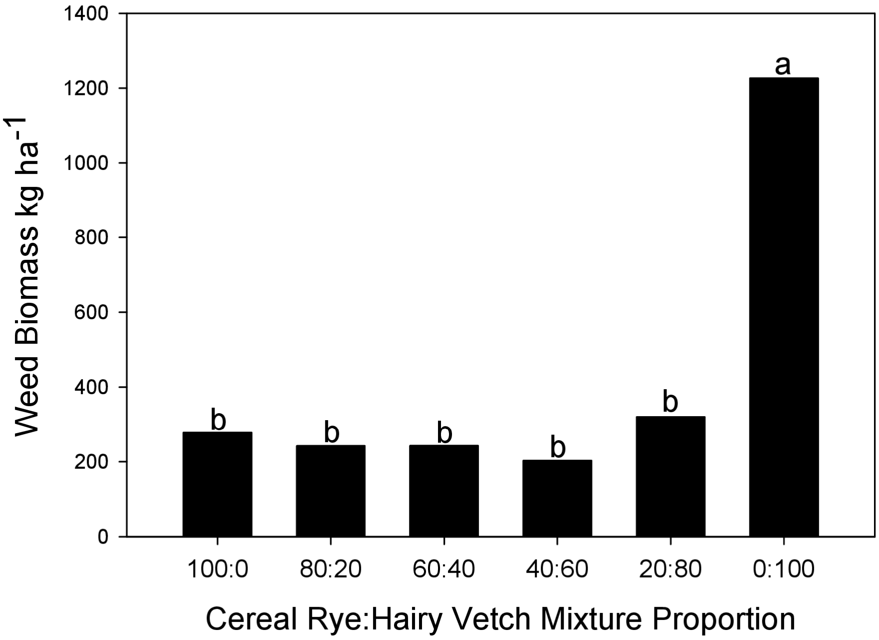

Figure 5. Weed biomass at corn silking over the 2013–2014 growing seasons under different cereal rye/hairy vetch mixture proportions (data from the Agricultural Research Center, Beltsville, MD, USA). Different letters above bars show significant differences ($F_{5,18} = 4.57$, $p < 0.01$).

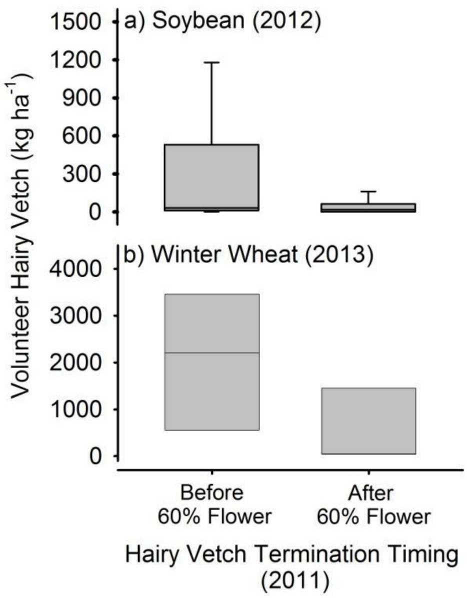

Figure 6. Effect of hairy vetch termination timing in 2011 on volunteer hairy vetch abundance in the following soybean (2012) and winter wheat (2013) cash crops averaged across Pennsylvania and Maryland locations (data from the ROSE). Hairy vetch termination ranged from the vegetative stage to 100% flowering on the last five nodes below the apical meristem.

The timing of cover crop termination also has important implications for the management of seed and seedling invertebrate pests in CCORNT systems. At the Pennsylvania ROSE location, corn seedling herbivory increased as cover crop termination was delayed in some years, but was highly variable across termination timings in no-till soybean [56]. The primary herbivores contributing to corn seedling damage were black cutworm (*Agrotis ipsilon* Hufnagel) and slugs (Mollusca). In this case, greater herbivore activity in late-planted corn may be attributed to herbivore response to higher temperatures. However, cover crop management also influenced the activity of ground-dwelling natural enemies of arthropod pests [57]. In particular, greater activity-density of large ground beetles (Coleoptera: Carabidae) occurred as termination of hairy vetch/triticale and cereal rye cover crops were delayed. Moreover, carabid activity-density and species richness increased each year during the three-year transition to organic production. The design of integrated, multi-tactic pest management approaches likely requires a greater understanding of early-season insect pest dynamics in CCORNT systems for the primary pests in the mid-Atlantic region, including wireworms (Coleoptera: Elateridae), seed corn maggot (*Delia platura*) and cutworms (Lepidoptera: Noctuidae). However, limited evidence suggests that CCORNT systems may provide suitable habitat for predatory arthropods, thereby providing measurable levels of conservation biological control.

3.2.4. Corn Fertility Management

Similar to tillage-based corn production, the N needed by the corn crop in CCORNT systems comes from cover crops, soil mineralized N and other sources of supplemental N (e.g., animal byproducts or Chilean nitrate). The proportion of these N sources used by producers depends on the cover crop, its management, past management history and soil type. Hairy vetch can supply over 180 kg ha^{-1} of plant N from the shoots alone, with over 90 kg ha^{-1} of that being plant available [48,52,58,59]. Previous studies have suggested that a monoculture of hairy vetch can supply the full N requirements of a corn crop on heavier soils that have a long history of manure and legume use [60], which can be attributed to the high N supplying capacity of the soil supplementing the legume-based fertility. Local recommendations are that producers not rely on a cover crop alone to meet corn N demand. This is particularly necessary when working with cereal rye/hairy vetch mixtures. Mixtures at 50% legume biomass and higher will produce comparable total shoot N levels to a legume monoculture [58], but with each incremental increase of grass in the mixture, there is a shift in the C:N ratio of the residue. Lower C:N ratio residues decompose rapidly with subsequent early release of N, while higher C:N ratio residues take longer to decompose and delay N release [52,61]. The timing of N release is critical. If N is released too early, prior to when corn enters its peak N demand phase (at approximately the corn six-leaf stage, V6 [62]), the N is susceptible to environmental loss via leaching and gaseous emissions. If N is released too late, it will not provide appropriate nutrition for the corn crop, negatively affecting corn production. Thus, for legume-based cover crops to be an effective N source and to reduce N-loss from agricultural lands, the synchrony of N release with crop physiological demand is vital [63]. The use of a grass in combination with a legume cover crop can improve N-release synchrony. Prior to termination, grass cover crops may take up N produced by legumes, while after termination, the higher C:N ratio of grasses moderates the leaching potential of the low C:N-ratio legumes [64,65]. Recent research in Maryland demonstrated that mixtures of hairy vetch and cereal rye, residues of which have a substantively higher C:N ratio than hairy vetch alone, can slow the decay rate of cover crop residues and reduce the quantity of early season plant-available N in the soil while still providing an important source of N for corn later in the season [52,58]. However, while maximum N content is maintained up to a 50:50 grass/legume mixture (based on biomass), the quality of the material results in lower overall plant-available N during the growing season and necessitates the addition of poultry litter or dairy slurry as used in the ROSE.

The addition of poultry litter or dairy slurry helps to ensure adequate N for a following corn crop, but adds to management complexity. In tillage-based systems, cover crops and animal byproducts are incorporated prior to cash crop planting. Applying animal byproducts poses numerous logistical and environmental difficulties in no-till production. Applying animal waste onto surface mulches increases their decomposition rates [52], speeding potential N leaching from the cover early in the spring when corn N uptake is small. However, decreasing the amount of surface biomass levels via tillage (i.e., to incorporate animal byproducts) will also reduce the amount of cover crop surface biomass present to suppress weeds. Furthermore, the mid-Atlantic region encompasses multiple sensitive watersheds in which regulations dictate manure application management and timing. For example, in the state of Maryland, animal byproducts like poultry litter are not allowed to be surface-applied unless they are incorporated within 48 h. Therefore, N contributions from cover crops remain important to reduce the amount of supplemental N required from animal byproduct sources. The N:P ratio of legumes or grass/legume mixtures offsets the N:P ratio of animal byproducts, which tend to increase soil P when applied at N replacement rates. Not only is it expensive to apply animal byproducts such as liquid dairy manure and poultry litter at N replacement levels, but soil P levels are highly regulated in the mid-Atlantic region. Organic farmers who have historically applied large quantities of organic amendments can build up their N mineralization potential [66]. In cropping systems with a history of cover crop use and organic amendment application, organic grain farmers can produce medium corn yields of 8000 kg ha^{-1} on soil mineralized N alone [67].

4. Ongoing Challenges and Conclusions

CCORNT systems can provide high-value and in-demand agricultural products while potentially improving soil health and protecting regional watersheds via improved nutrient management. In the last five years, significant progress has been made in improving the viability of these cropping systems in the mid-Atlantic region of the U.S. For soybeans, CCORNT production holds particular promise now that improved planter technology has increased crop performance and competiveness against weeds and high-residue cultivators are commercially available to manage perennial and annual weeds not controlled by the mulch. However, major constraints to CCORNT corn production remain, given the complexity of balancing soil fertility and weed management demands. Large amounts of cover crop residue (especially grass residue) are needed to suppress weeds, but such residue can interfere with cash crop establishment and immobilize soil N, decreasing corn yields. In the case of corn, legume-grass cover crop mixtures better balance soil fertility and weed management goals, but present management complexities of their own, including: (1) current crop planter designs struggle to plant into cover crop mixtures; (2) there are few legume options that are compatible with roller-crimping, and viable species like hairy vetch present the risk of regrowth and weediness in future cash crops; and (3) limited economically viable, production-ready equipment that can apply animal by-products in high-residue no-till production systems. Moreover, CCORNT systems suffer from reduced flexibility relative to tillage-based organic systems, due to the limited windows of opportunity for controlling cover crops.

The lack of availability of effective machinery and machinery configurations to plant cash crops into heavy cover crop residue continues to be a major constraint [14]. Unlike conventional producers, organic farmers must maximize the above-ground cover crop biomass for weed suppression. Planter technology must effectively deal with in-row plant material. A recent survey of organic farmers in upstate New York found that many are having to custom develop their own cultivation equipment in response to the lack of research and development on new machinery [68]. As outlined above, large quantities of cover crop biomass are generally required for effective weed control. This constitutes substantial surface mulch that must be cut through to ensure effective seed-soil contact to maximize cash crop germination and establishment. Planter configurations require flexibility to be optimized for effective seed placement depending on local environmental conditions and cover crop performance in a given year. Moreover, more research is required to elucidate region-specific practices related to the timing and combination of roll/plant and roll-roll/plant operations. This will ensure the efficacy of cover crop termination (i.e., minimizing volunteer cover crops), weed suppression and cash crop establishment [35,50]. As data from the ROSE demonstrate, the development of effective high-residue cultivation machinery can potentially allow for lower quantities of cover crop biomass while still providing comparable levels of weed control. However, a tradeoff exists between achieving sufficient cover crop biomass and conducting more frequent high-residue cultivation. Greater cover crop biomass provides effective weed suppression, soil protection and a valuable N source; more frequent high-residue cultivation reduces residue residence time and soil protective benefits and can increase asynchrony between residue N release and cash crop N demand.

Beyond machinery development and its effective implementation, there is also a need for improved cover crop germplasm and management practices [69,70]. Cover crops have not benefited from the same intensive breeding scrutiny as cash crops and consequently show wide variation in agronomic traits and the ability to provide desirable ecosystem services. A recent survey of farmers across the U.S. identified numerous desirable cover crop traits upon which breeding efforts should focus, including N-fixation (for legumes), winter hardiness, early vigor and establishment, biomass production and weed suppression [71]. Improved cover crop germplasm, including the development of highly adapted regional varieties [72], would allow for greatly improved integration and management of cover crops within existing cropping systems, particularly as they relate to cover crop phenology and termination timing [21,29]. Greater standardization of leguminous cover crops would aid the development of more reliable N management recommendations and advance our ability to predict how fixed N contributes to subsequent corn yield [73], particularly when legumes are grown in mixtures with grasses. More research is also required to understand the allelopathic properties of cover crops and how they can be effectively managed to maximize weed suppression while minimizing negative impacts on cash crops. For example, zonal management of cover crop residues, where residues are moved from crop rows to inter-rows prior to cash crop planting, may help minimize negative allelopathic effects on the cash crop while enhancing weed suppressive effects in inter-rows [74]. However, this would have to be balanced with the need to ensure adequate mulch for weed suppression in crop rows.

Lastly, more research is required to elucidate the potential of CCORNT production systems to improve soil health. Tillage-based organic agriculture has often been found to build soil health, e.g., have increased soil organic matter (SOM), soil C and N and microbial biomass and activity relative to conventional systems [75,76]. However, organic systems typically rely on frequent and intensive tillage operations to control weeds, which can undermine the ability of organic systems to build soil health [12,68,77]. No-till agriculture, which eschews tillage and typically relies on herbicides for weed control, has been found to conserve soil health compared with tillage-based agriculture, leading to enhanced SOM in surface soil, microbial biomass and activity [78,79]. However, over-reliance on herbicides has resulted in a growing list of herbicide-resistant weed species that threatens crop production across the U.S. [80]. CCORNT may offer a bridge between tillage-based organic and no-till systems. By attempting to integrate the soil building properties of tillage-based organic agriculture with the soil conservation properties of no-till, CCORNT may enhance soil health while minimizing the drawbacks of tillage-based organic systems. In addition, by employing a multi-tactic weed management approach, CCORNT may represent a long-term sustainable crop production system and offer valuable insights for contemporary conventional and no-till production systems on methods to counter the increasing prevalence of herbicide-resistant weeds.

Supplementary Materials: The following are available online at www.mdpi.com/2077-0472/7/4/34/S1, Table S1: Soil type and crop production history for experimental locations.

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