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A Decade of Progress in Organic Cover Crop-Based Reduced Tillage Practices in the Upper Midwestern USA

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Abstract: The organic industry continues to expand in the United States (U.S.), with 14,093 organic farms in 2014. The upper Midwestern U.S. has emerged as a hub for organic row crop production; however, the management of these organic row crop hectares heavily relies on tillage and cultivation for weed control. Faced with the soil quality challenges related to these practices, and cognizant of the benefits of conventional no-till practices, organic farmers have shown significant interest in the development of Cover Crop-Based Reduced Tillage (CCBRT) techniques to lessen soil disturbance while achieving successful weed management. To serve this farmer interest, significant research efforts have been conducted in the upper Midwestern U.S., focused on systems-based practices to ensure adequate suppression of weeds, through a combination of agronomic and cover crop species and variety selection. Within this review article, we discuss the agronomic successes that have been achieved in CCBRT using a combination of cereal rye and soybeans, resulting in consistent suppression of weeds while providing fuel and labor savings for farmers, as well as the continued challenges that have persisted with its implementation. Continued investment in research focused on cover crop breeding and management, optimization of CCBRT equipment and fertility management, and a greater understanding of rotation effects will contribute to the further expansion of this technique across organic farms.

Keywords: organic agriculture; cover cropping; reduced tillage; ecosystem services; USA

1. Introduction

The organic industry continues to expand in the United States (U.S.), with 14,093 certified organic farms in 2014 [1–3]. The 2014 National Agricultural Survey of organic production, conducted by the United States Department of Agriculture (USDA), reported 82,328 hectares of organic corn and 39,996 hectares of organic soybean among the 1.4 million organic cropland and vegetable hectares in the U.S. [1].

Management of these organic row crops heavily relies on tillage and cultivation for weed control. While mechanical practices can be effective to manage weeds, these activities prevent organic farmers from fully optimizing the requirement for soil building, as set forth in 7 CFR §205.203 and 205.205 of the National Organic Program (NOP) [4]. In typical organic row crop production in the upper Midwestern U.S., five to six tractor passes with tine weeders, rotary hoes, and/or row cultivators are often necessary for adequate weed control, which can negatively impact soil aggregation and soil organic matter concentrations, while exposing the land to greater risk of erosion. Additionally, the reliance on cultivation as a primary weed management tool poses risks during wet springs, an increasingly common production challenge with heavy rainfalls occurring more frequently as a result of climate change [5]; consistently wet soil conditions can prevent organic producers from implementing timely weed management through cultivation, increasing weed competition and weed seedbanks while negatively impacting yields. Ongoing data from the Wisconsin Integrated Cropping Systems Trial, a long-term management trial begun in 1989, illustrates that while organic management results in comparable yields to conventional management during more moderate production seasons, years exhibiting wet spring conditions result in yields of corn and soybeans falling to approximately 75% of those produced using conventional practices, due to the inability of farmers to conduct timely weed management [6].

In addition to weed management challenges associated with tillage and cultivation, these practices can also increase the risk for soil erosion. Several Midwestern regions of the U.S. which support high concentrations of organic farms, including the Driftless regions of Wisconsin, Iowa, and Minnesota, are characterized by farm fields exceeding 4% or greater slopes. The soils in these regions vary widely, from heavy, poorly drained clay soils to sandy, shallow, droughty soils. These conditions create a landscape susceptible to erosion, negatively impacting both soil and water quality of several key watersheds, including the Mississippi Valley Watershed.

Conventional no-till farming techniques have been promoted for their role in reducing water runoff and soil erosion, as well as maintaining soil carbon [7,8], although the degree and nature to which the conventional no-till systems build soil C, and the degree to which this C is stably stored, can vary [9,10]. No-till systems can also increase infiltration of water into the soil by 25 to 50% compared with conventional tillage systems [11]. In addition, cover crop surface residues can decrease the effect of wind and temperature on soil water evaporation, increase water storage in the soil profile [12,13], scavenge available nitrogen, and prevent soil erosion [14], thus preventing watershed contamination and nutrient losses [14,15].

Faced with the soil quality challenges associated with tillage and cultivation, and cognizant of the benefits of conventional no-till practices, organic farmers have shown significant interest in the development of no- and reduced-tillage techniques suitable for organic production. Within the majority of the reduced tillage systems currently utilized by organic farmers, no-till phases are incorporated throughout the rotation, with tillage limited to establishing the cover crops [16–18]. This technique, often referred to as Cover Crop-Based Reduced Tillage (CCBRT) uses mature cover crop residue as a mulch to smother weeds, replacing the standard organic weed management tactics of tillage and cultivation. Winter annual cover crops (typically cereal rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* L.)) are seeded in the fall and terminated mechanically without herbicides in the spring, often using a roller-crimper (Figure 1a) which creates an in situ surface mulch that physically suppresses weeds. At the time of cover crop termination, the cash crop (typically soybean (*Glyine max* (L.) Merr.) or field corn (*Zea mays* L.)) is planted directly into the cover crop mulch (Figure 1b), which provides season-long weed suppression without further soil disturbance throughout cash crop production.

(**a**)

(**b**)

Figure 1. (**a**) Photograph of the roller-crimper design commonly used by farmers and researchers in the upper Midwestern U.S.; (**b**) Photograph of soybeans emerging through the rolled winter cereal rye mulch.

2. Organic Cover Crop-Based Reduced Tillage in the Upper Midwestern U.S.

The upper Midwestern U.S. maintains a long history in organic farming, and still remains a primary center of the U.S. organic industry [1]. Prior to the rise of organic agriculture, regional environmental leaders, such as Aldo Leopold, an ardent environmentalist, and Gaylord Nelson, a Wisconsin politician, inspired a strong land ethic in upper Midwestern culture. Counter to the argument that the maturation of the organic industry will, by default, lead to a concurrent conventionalization of the industry, the production practices used by upper Midwestern organic farmers demonstrate adherence to the soil-building ethic that serves as a foundation of the organic regulation outlined by the NOP [19].

CCBRT research began in the early 2000s in the upper Midwest, with several research programs, including Iowa, Wisconsin, and Michigan, establishing experimental plots both at land-grant university research stations and on working certified organic farms. Research approaches have predominantly centered on techniques and equipment made popular by the Rodale Institute in Kutztown, PA, where a fall-planted cover crop is mechanically terminated in the spring (cereal grains at anthesis at Zadok's growth stage 60, or legumes at 100% bloom). Cover crop termination is achieved with a roller-crimper, a hollow steel cylinder with metal slats arranged in a chevron pattern, welded at uniform spacing along the length of the drum that can be filled with water for added weight [20–22] (Figure 1a). However, research programs have also included cover crop termination treatments that utilize sickle-bar mowing and flail mowing [20,22].

Much of the CCBRT research in the upper Midwestern U.S. has focused on systems-based practices to ensure effective suppression of weeds, primarily through a combination of agronomic practices and cover crop management. Corn and soybean have been the primary commodity crops that have been evaluated within the CCBRT system in this region. However, studies have also addressed other critical aspects of the system, including cash crop yields, economic assessments regarding fuel and labor savings, and reduction in erosion risk.

As research data is generated and practical experiences are reported by organic farmers, CCBRT has also been not only gaining recognition, but is being implemented across the organic agricultural landscape. According to the 2014 USDA Organic Survey, organic farmers in the upper Midwest are increasingly adopting organic no-till management strategies as part of their farming practices. Of the 3319 certified organic farms in of Iowa, Illinois, Michigan, Minnesota, Missouri, Nebraska, and Wisconsin, 957 reported the use of no-till practices [1]. This survey, however, does not provide adequate resolution to determine whether CCBRT practices in row crops are being used, or whether other no-till practices are being reported, such as reseeding grasses and legumes into existing pastures without tillage. On a state level, the reported use of no-till practices ranged from 20 to 37% of organic farms (Iowa: 27% (166 no-till farms, 612 total organic farms); Illinois: 27% (69, 249); Michigan: 20% (67, 332); Minnesota; 37% (189, 512); Missouri: 28% (61, 216); Nebraska: 32% (54, 170); Wisconsin: 29% (351, 1228)) [1].

The remainder of this paper summarizes experiences with CCBRT in the upper Midwestern U.S., incorporating published results from research studies and on-farm observations. Several platforms exist from which data and information are assembled: (1) land grant University research programs, particularly the efforts in Wisconsin and Iowa; and (2) organic farmer networks and participatory research efforts, such as OGRAIN (the Organic Grain Resource and Information Network), led by the University of Wisconsin-Madison. Further, the authors discuss remaining barriers in the CCBRT system which prevent more wide scale adoption in the upper Midwestern US, and further research needs necessary to address those barriers.

3. Summary of CCBRT Research in the Upper Midwestern U.S.

3.1. Organic Soybean Production

Weed management in organic cropping systems remains a significant challenge for organic farmers, particularly in the soybean phase of a typical corn–soybean-winter wheat–alfalfa rotation common to organic grain systems in the upper Midwestern U.S. [21,22]. Unlike corn and winter wheat, which develop above-ground biomass early in the growing season and thus more effectively compete with weeds, soybean crops, often planted on the wider row spacing for cultivation, can be relatively slow to canopy, allowing weeds to establish over a prolonged period during the first half of the production season. As such, the development of CCBRT techniques for this phase of the crop rotation to augment mechanical weed management strategies during soybean production addresses a critical production challenge.

CCBRT research in organic soybean production in the upper Midwestern U.S. have integrated the establishment of a cereal grain cover crop (most often cereal rye) in late summer or early fall, typically seeding at a rate of 180–269 kg·ha^{-1} [20,22] (Table 1). The cereal grain cover crop is then terminated in late spring, with soybean directly seeded through the cereal grain mulch, at rates of 500,000 seeds·ha^{-1}; or more. Other cereal grain cover crops have also been trialed for use in CCBRT, including Winter triticale (*Tritocosecale* Wittm. Ex A Camus), winter barley (*Hordeum vulgare* L.), 'McGregor', and winter wheat (*Triticum aestivum*) [21,22].

While CCBRT has demonstrated its ability to effectively suppress weeds in organic soybean production [20,22], the capacity of the cover crop residue to prevent weeds from establishing varies widely depending on the weed species present in the field. Small-seeded annual broadleaf weeds tend to be suppressed more easily by the mulch and thus are more dominant in tilled organic systems [23–25]; if fields have adequate mulch biomass and complete cover crop termination, up to 80% control of common annual weeds in winter rye stands have been reported [26]. Perennial weeds are less sensitive to suppression by the mulch and readily proliferate in the system over time [25,27].

Weed management using the CCBRT technique is comprised of diversified approaches, with efficacy driven by rye biomass levels, cash crop planting date, seeding rate and placement, and cash crop stand establishment. Under typical cropping conditions, rye can produce biomass levels that range from 4000−11,000 kg·ha^{-1} [22] (Table 1). Research has demonstrated that in order to reliably suppress weeds as a surface mulch, the fall-planted cereal grain cover crop must reach biomass levels at the higher end of this range, ideally exceeding 8000 kg·ha^{-1} [26,28]. This allows the mulch to effectively limit weed populations by not only physically interfering with the emergence process, but also preventing the breaking of seed dormancy and inhibiting weed germination through allelopathy [27].

While CCBRT systems can produce soybean yields that are within state averages for organic soybeans, yields continue to lag behind organic systems that are managed using typical tillage practices. Research in Iowa and Wisconsin has demonstrated that, while during some seasons CCBRT yields are not significantly different than typically managed organic soybean, in many circumstances yield reductions in CCBRT systems as compared to typical organic soybean yields are observed, even with planting dates remaining the same, with up to a 24% or more reduction in yields observed [20,21]. Reasons for these observed yield reductions may be multi-fold: (1) cooler soil temperatures under the rye residue delaying soybean germination; (2) slower or inhibited root growth under the rye mulch; (3) nutrient tie-up under the rye mulch; and (4) allelopathic effects of the cereal rye. Whereas soybean biomass at the end of the production season is similar between CCBRT and typically managed organic soybean, early season growth of CCBRT soybeans has been observed to be slower as compared to typical organic production practices. As the weed pressure experienced within the two systems has been observed to be either equivalent or less in the CCBRT, it is unlikely that weed competition is a primary factor resulting in the observed yield differences.

Table 1. Summary of results of Cover Crop-Based Reduced Tillage (CCBRT) research conducted in the upper Midwestern U.S.A. as reported in peer-reviewed research journals.

Study Location	Cover Crop Variety	Cover Crop Planting Date [1]	Cover Crop Seeding Rate and Row Spacing	Cover Crop Termination Date	Cover Crop Biomass at Termination	Cash Crop Seeding Rate and Row Spacing	Cash Crop Planting Date	Weed Populations/ Biomass	Cash Crop Stand Populations	Soybean Yields	Citation
Soybean ((Glycine max (L.) Merr.))											
Iowa	Cereal rye (*Secale cereale* L.), Variety Not Specified (VNS)/VNS hairy vetch (*Vicia villosa* L.)	12 September and 31 October	72 kg·ha^{-1} cereal rye, 36 kg·ha^{-1} hairy vetch	Zadoks growth stage 60	N/A [2]	494,210 seeds·ha^{-1}; 76 cm rows	23–25 May	7–8 weeds·m^{-2}	226,719–308,733 plants·ha^{-1}	1067–2724 kg·ha^{-1}	[21]
	Winter wheat (*Triticum aestivum* L.) ('Expedition' and 'Arapahoe'/winter pea (*Pisum sativum* subsp. Arvense) cover crop)	12 September and 31 October	63 kg·ha^{-1} winter wheat, 21 kg·ha^{-1} Winter Pea	Zadoks growth stage 60	N/A	494,210 seeds·ha^{-1}; 76 cm rows	23–25 May	9–15 weeds·m^{-2}	209,422–275,357 plants·ha^{-1}	628–5668 kg·ha^{-1}	[21]
Wisconsin	Cereal rye, 'Rymin'	5 October and 7 October	180 kg·ha^{-1}, 19 cm row spacing	6–11 June	4.3–10.8 Mg DM·ha^{-1}	625,200 seeds·ha^{-1}; 19 cm row spacing	18–21 May	3–229 kg·ha^{-1}	377,100–505,600 plants·ha^{-1}	2751–2885 kg·ha^{-1}	[20]
	Hairy vetch, 'VNS'	8 September and 13 September	33.6 kg·ha^{-1}, 19 cm row spacing	28 May–8 June	3.7–5.0 Mg·DM·ha^{-1}	N/A	N/A	4–47 weeds·m^{-2}	N/A	N/A	[22]
	Winter rye, 'VNS'	8 September and 13 September	269 kg·ha^{-1}, 19 cm row spacing	28 May–8 June	10.2–10.3 Mg·DM·ha^{-1}	N/A	N/A	1–25 weeds·m^{-2}	N/A	N/A	[22]
	Winter triticale (*Tritocosecale* Wittm. Ex A Camus), 'Fridge'	8 September and 13 September	269 kg·ha^{-1}, 19 cm row spacing	28 May–8 June	6.4–14.6 Mg·DM·ha^{-1}	N/A	N/A	24–26 weeds·m^{-2}	N/A	N/A	[22]
	Austrian winter pea (*Pisum sativum* subsp. arvense), 'VNS'	8 September and 13 September	44.6 kg·ha^{-1}, 19 cm row spacing	28 May–8 June	0–6.3 Mg·DM·ha^{-1}	N/A	N/A	0–18 weeds·m^{-2}	N/A	N/A	[22]
	Winter barley (*Hordeum vulgare* L.), 'McGregor'	8 September and 13 September	269 kg·ha^{-1}, 19 cm row spacing	28 May–8 June	10.3–11.7 Mg·DM·ha^{-1}	N/A	N/A	19–43 weeds·m^{-2}	N/A	N/A	[22]
Corn (Zea mays L.)											
Iowa	Cereal rye (*Secale cereale* L.), Variety Not Specified (VNS)/VNS hairy vetch (*Vicia villosa* L.)	12 September and 31 October	72 kg·ha^{-1} cereal rye, 36 kg·ha^{-1} hairy vetch	Zadoks growth stage 60	N/A	79,073 seeds·ha^{-1}; 76 m rows	23–25 May	N/A	45,302–59,510 plants·ha^{-1}	628–5668 kg·ha^{-1}	[21]
	Winter wheat (*Triticum aestivum* L.) ('Expedition' and 'Arapahoe'/winter pea (*Pisum sativum* subsp. Arvense) cover crop)	12 September and 31 October	63 kg·ha^{-1} winter wheat, 21 kg·ha^{-1} winter pea	Zadoks growth stage 60	N/A	79,073 seeds·ha^{-1}; 76 cm rows	23–25 May	N/A	49,824–51,479 plants·ha^{-1}	640–5567 kg·ha^{-1}	[21]

[1] Ranges of values in a given column reflect data from separate years in a given study, due to significant year effects [2] N/A: designates data not included in publication.

3.2. Organic Corn Production

Experimentation with CCBRT in the corn phase of the crop rotation has primarily differed with respect to the cover crop used in the system. Whereas the same planting strategies are used—a winter-hardy cover crop is seeded in the late summer and terminated during the following spring—CCBRT techniques for corn have integrated the leguminous cover crops, occasionally in combination with a cereal grain to enhance mulch biomass [21,22] Hairy vetch (*Vicia villosa* L.) has been the most commonly researched and trialed legume cover crop in the corn CCBRT system, although alternative legumes such as Austrian winter pea and field pea (*Pisum sativum* subsp. arvense) have also been tested [21,22]. Seeding dates of these legume cover crops have been similar to those used in the establishment of cereal grain cover crops (late summer/early fall), with seeding rates ranging from 33.6–44.6 kg·ha^{-1}.

As with the effective mechanical termination of cereal grain cover crops, legume cover crops must be terminated at specific maturities. To obtain effective termination, roller-crimping or mowing must occur at 100% bloom to early pod set [29,30]. In the upper Midwest, this growth stage varies from late May (Austrian winter pea) to mid-June (hairy vetch) [22]. While a late May planting date can allow for corn grain and silage production. If appropriate short-season varieties of corn are used, mid-June planting dates substantially decrease the yield potential of organic corn, for both silage and grain. Within the Austrian winter pea cultivars that are commercially available, winter-hardiness remains marginal in the region, thus reducing the feasibility of this cover crop into the CCBRT system. With hairy vetch remaining the only reliable option for an overwintering legume cover crop which produces adequate biomass for an effective weed-suppressive mulch, CCBRT organic corn systems remain challenging if not prohibitive.

CCBRT in the corn phase has also proven more challenging than soybean due to increased risk of insect pest interactions. In research trials at the University of Wisconsin Arlington Agricultural research station, CCBRT corn stands have been decimated by army worm (*Mythimna unipuncta* Haworth), particularly when cover crop stands have included a cereal grain. This insect pest, which oviposits on the lower leaves of grasses or the base on grass plants, can be attracted to the cereal grain cover crop during its migration from the southern states of the U.S. Depending on the timing of this migration, newly hatched larvae may emerge from the cover crop residue at the time of corn germination, then feeding upon the corn seedlings. Although it has not been observed, depending on annual conditions and insect life cycles, a similar risk exists with seed corn maggot (*Delia platura* Meigen), a common corn insect pest. which lays eggs on decaying vegetation in late April or early May. Without the option to use chemical insecticide seed treatments, the development of CCBRT strategies must account for ecological-based management solutions, such as avoiding the use of cover crops that are preferred hosts to insect pests and the altering of cash crop planting dates to avoid specific pest cycles, to mitigate the risk of insect damage to the cash crop.

3.3. Economics and Labor/Fuel Savings

Several CCBRT studies conducted in the upper Midwestern U.S. have integrated economic analyses into their data analysis (Table 2). In an analysis conducted by Bernstein et al. [20], returns to labor, capital, and management of the CCBRT treatments using cereal rye were 27% less than in the organic tilled system, primarily due to the 24% yield reduction shown in this particular study. However, the study also documented that labor and fuel inputs were reduced by nearly 50% in the no-till cereal rye treatments. Although the profitability per hectare was greater in the tilled treatment, the return per labor hour was 25% greater in the no-till cereal rye system. These savings not only translate to economic savings, but could have positive impacts on the farmers' quality of life, potentially allowing them to engage in other enterprises or expand their soybean acres. Significant diesel fuel savings were also documented, with 720 L of diesel fuel saved using no-till techniques. Delate et al. [21] found similar results, with significantly less labor costs in the CCBRT systems. As with the Bernstein study, returns to land and management remained less in the CCBRT systems as compared to the typical organic management systems, due to persistent soybean yield reductions.

Table 2. Economic analyses of CCBRT systems in the upper Midwestern U.S.

Study Location	Cash Crop	Cover Crop	Cash Crop Row Spacing	Yields kg·ha^{-1}	Gross Revenue USD·ha^{-1}	Return to Management USD·ha^{-1}	Citation
Iowa	Soybean	Cereal rye/hairy vetch	76 cm	1067–2724 [1]	672–1769	−63–993	[21]
		Winter wheat/winter pea		1042–2862	656–1859	36–1198	
		No cover crop (traditional tillage)		2197–3170	1383–2059	742–1377	
	Corn	Cereal rye/hairy vetch	76 cm	628–5668	217–1394	−660–527	
		Winter wheat/winter pea		640–5567	221–1369	−540–618	
		No cover crop (traditional tillage)		7777–9710	2389–2694	1602–1866	
Wisconsin	Soybean	Cereal rye	19 cm	2751–2885	N/A [2]	1598–1687	[20]
		No cover crop (traditional tillage)	76 cm	3618		2162	

[1] Ranges of values in a given column reflect data from separate years in a given study, due to significant year effects.
[2] N/A: designates data not included in publication.

The CCBRT studies focused on organic corn are much more limited. Delate et al. [21], over two years of investigating CCBRT strategies using hairy vetch/rye and winter wheat/winter pea, found return to management to range from an economic loss (−660 USD·ha^{-1}) to more profitable scenarios (618 USD·ha^{-1}) (Table 2). In both years over both production systems, however, return to management was significantly less than the tilled organic corn systems (1602–1866 USD·ha^{-1}).

3.4. Impact of CCBRT on Soil Quality Parameters

The adoption of reduced-tillage practices such as CCBRT has been promoted as a tool to mitigate soil C loss, build soil organic matter (SOM), and reduce the risk of erosion [31]. However, in large part due to the lack of long-term organic CCBRT experimental sites, the impact of CCBRT techniques on increasing soil C and SOM remains unclear. Clark et al. (2017) [32], investigating the impact of CCBRT techniques on soil parameters in organic row crop production in Missouri, USA, reported no change in soil organic carbon (SOC) under CCBRT management, but concluded this may be due to the short two-year time frame of the experiment. Using the Revised Universal Soil Loss Equation, Version 2 to predict soil loss, Bernstein et al. [20] estimated that the CCBRT soybean plots integrating cereal rye as a cover crop would result in a soil loss of 1.5 Mg·ha^{-1} on a 1.0% slope and 5.6 Mg·ha^{-1} on a 4.5% slope, significantly less than the predicted soil loss on the organic till soybean fields, which ranged from 10.9 Mg·ha^{-1} on a 1.0% slope to 49.3 Mg·ha^{-1} on a 4.5% slope. While not measured directly, these same models predicted changes in soil organic matter (soil conditioning index, on a scale of −2 to +2), were positive in CCBRT rye treatments (+0.4 on 1.0% slope and +0.3 on 4.5% slope) and negative in the tilled rye treatment for both slope grades, (−0.9 on 1.0% slope and >−2.0 on 4.5% slope).

While benefits are predicted with respect to building SOM and minimizing erosion, nutrient availability dynamics may be negatively impacted during the soybean production season. In the aforementioned Bernstein et al. study [20], plant tissue tests demonstrated that while soil nutrient concentrations were similar among CCBRT and tilled soybean treatments, soybean uptake of N, P, and K as measured by tissue tests was several-fold greater in the tilled treatment as compared to the CCBRT treatments. These same results have been demonstrated in subsequent years on other fields at the University of Wisconsin Arlington Agricultural Research Station (data not published).

4. Challenges to Further Adoption of CCBRT in the Upper Midwestern U.S.

4.1. Adapting the CCBRT System to Organic Rotations

While the use of CCBRT has demonstrated success in the soybean phase of the rotation using cereal grain cover crops, strategizing crop rotations that are both agronomically and economically sound remains a challenge for organic farmers in the upper Midwestern U.S. A typical representative rotation may include corn–soybean-winter wheat–alfalfa, with corn harvested either as a silage crop throughout September or as a grain crop from late September into October. Research has demonstrated that cereal rye planting date in the fall significantly impacts ground cover in early spring and biomass at termination at anthesis (Zadoks stage 60), two factors critical to ensuring weed suppression throughout the soybean production season [27]. Thus, an organic crop rotation that includes a CCBRT soybean phase would be limited to a rotation that incorporates silage corn as opposed to grain corn in the more northern areas of the upper Midwestern U.S., if the farm were to follow a typical organic rotation scheme. While this is a viable option for organic livestock farmers utilizing CCBRT techniques, it creates a less economically viable rotation for organic cash grain farmers.

Interactions of CCBRT with the winter wheat is also of concern with respect to rotation management. While cereal rye can be planted after a winter wheat and oat harvest, this rotation may not be ideal as it results in sequential cereal grain plantings, which can increase the risk of certain plant diseases. A CCBRT rye-soybean phase into a typical corn–soybean-winter wheat rotation can also have negative repercussions on the subsequent winter wheat crop. With planting dates delayed 2–3 weeks from typical organic yields to synchronize with the appropriate cereal rye maturity stage, CCBRT delays soybean maturity, with harvest occurring in late-October versus late September or mid-October. With much of the high-carbon cereal rye residue remaining at soybean harvest, this further creates delays of winter wheat planting, which typically occurs between mid and late October. This delay in field preparation may result in the need to shift to spring-planted cereal grains, such as oat or spring wheat, which typically result in lower yields and quality as compared to winter cereal grains grown in the regions of the upper Midwestern U.S. with higher precipitation.

Additionally, some farmers utilizing CCBRT in a rye/soybean phase of the rotation have experienced contamination issues in their subsequent cereal grain crop. If the termination of the cereal rye is not completely effective, cereal rye plants producing viable seed may emerge within the soybean crop. While not having a negative impact on the soybean phase, these seeds may germinate in the subsequent cash crop year, resulting in volunteer cereal rye plants. If another cereal grain crop, such as winter wheat, is sown into this field, unacceptable levels of contamination by rye seed at harvest may cause the product to be rejected. While this is less of an issue for livestock farmers feeding the grain to their own herds, this can be a significant concern for farmers selling into the commodity grain market.

4.2. Fertility Management in CCBRT

The impact of cereal rye on soil inorganic nitrogen (N) availability and the subsequent impacts on both weeds and the soybean cash crop growth have just begun to be investigated. Fertility management can include both the cereal rye cover crop and the soybean cash crop. To achieve a desirable level of biomass of 8000 kg$\cdot$ha^{-1} or greater, the cereal rye cover crop requires at least 90 to 110 kg of available N$\cdot$ha^{-1}, if a desired shoot N concentration of 9–11 g N kg^{-1} is used [33,34]. To ensure that the cereal rye produces enough biomass to reliably suppress weeds, in some systems, fertilization of the cereal rye may be necessary.

Fertility management in high-residue environments presents specific challenges that need to be addressed in the CCBRT system. Research suggests that cold soil temperature conditions, such as those typically observed in the spring in CCBRT systems, can reduce nutrient mineralization and consequently yields. Work conducted in Wisconsin by Andraski and Bundy [35] concluded that soil temperature in no-till systems is the main factor affecting net N mineralization in corn systems, as opposed to N immobilization by residues, and recommended increasing N fertilization rates up to 30 kg·ha^{-1} for high residue no-till systems. In the rye/soybean system, CCBRT has been shown to lead to nutrient deficiency in the system as compared to typical organic management. Bernstein et al. (2011) [20] documented N and sulfur (S) deficiency in soybean tissue collected at the R1 growth stage grown under CCBRT in Wisconsin. Similarly, in 2013, Silva documented N deficiency in CCBRT soybean plots in Wisconsin through tissue testing conducted at the initial flowering stage, with tissue N averaging 3.5% and tissue S averaging 0.3% (unpublished data). Furthermore, in the studies of both Bernstein and Silva, visual symptoms of N deficiency were observed throughout the study period in the no-till treatments, from the vegetative cotyledon (VC) soybean stage to the reproductive 2 (R2) stage.

As continued efforts are dedicated to developing CCBRT for organic corn production, the issue of nutrient management in the system becomes even more critical. Unlike soybean, which can overcome some degree of initial N deficiency of the system as nitrogen fixation by rhizobium bacteria begins to occur, corn yields are more affected by insufficient N availability at critical stages of plant growth. With the incorporation of nitrogen-rich above and below ground biomass, legume cover crops can provide substantial N credits to the subsequent crop; however, in CCBRT systems where the aboveground biomass is not incorporated prior to cash crop planting, the N credit may be less than what might be anticipated from typical legume cover crop management. Options for supplemental N fertility may include topdressing or side-dressing with manure during the corn phase. However, in the high residue system where disturbance of the cover crop mulch can lead to exposed soil and subsequent weed establishment, the integration of these strategies may require equipment modification or novel application techniques.

4.3. Equipment Modifications

Even with cereal rye biomass reaching levels sufficient for effective weed suppression, potential yields of the system can be reduced due to poor soybean stands. Adequate seed placement through the thick cereal rye mulch is critical for the success of the system and is dependent on both environmental and physical factors. Equipment selection, modifications, and settings, as well as soil moisture at the time of planting, impact the ability of the planter to penetrate the mulch and achieve good seed-to-soil contact. Both conservation tillage planters and no-till drills have been used in the CCBRT system; planters, as compared to drills, are able to cut through the mulch while providing more precise seed metering and placement. Drills, however, can reduce the time to canopy closure due to narrow seed spacing [27,36]. If cereal rye residue is greater than 5000 kg·ha^{-1}, the planter is the preferred selection due to more effective mulch cutting [27]. Additionally, as the cover crops are typically planted at a high seeding rate, the cereal grains have a propensity to lodge prior to roller-crimping, making consistent seed placement difficult through the thick, uneven mulch using either equipment option.

Additional planter modifications can better ensure success with the CCBRT system. Extra weight can be added to the equipment to help ensure better cutting of the mulch residue and adequate seed placement. Coulters designed specifically for residue cutting, such as straight-edged coulters, can further facilitate planting and adequate seed-to-soil contact through the thick cereal rye residue. Initial evaluations with closing wheels has shown that a single 38-cm spiked closing wheel along with a smooth cast closing wheel on each row unit can help improve closure of the planting row [27]. In Wisconsin, several modifications have been made to the planter dedicated to CCBRT to contribute to more effective seed placement, including frame-mounted no-till coulters, and down-pressure springs, which increase planter weight, equivalent to 91 kg per row unit [37].

4.4. Planting Date Modifications

Research continues to be conducted to explore options beyond the foundational techniques developed by the Rodale Institute, which uses a one-pass operation at cover crop anthesis to roll-crimp the cover crop first and plant the cash crop through the cover crop residue. To improve the planting dates of the cash crop in the upper Midwestern regions where the production season length is limited, further work is being conducted to explore planting the cash crop prior to cover crop termination, providing a two to three-week advantage in cash crop planting. By planting into the standing versus rolled cover crop, seed placement may also be facilitated, mitigating the issue of poor seed to soil contact and lower cash crop stands. Initial work by Bernstein et al. [20] demonstrated yield improvements of over 130 $kg \cdot ha^{-1}$ with earlier versus later planted soybeans in CCBRT systems on narrow row spacing.

5. Future Developments in CCBRT Research

Research data collected over multiple years and multiple sites in the upper Midwestern U.S. indicate that the CCBRT system can be a viable and productive option for organic row crop farmers. Of all the potential cover crop and cash crop combinations, cereal rye and soybean remains the most consistent with respect to weed suppression and yields. While implementing CCBRT in the corn phase currently remains a less viable option, farmers continue to express interest in developing techniques that would allow for acceptable yields. Currently, the most significant barrier to successful CCBRT adoption in this phase is delayed cash crop planting dates. In order to ensure adequate nitrogen availability to the corn crop, as well as to mitigate pest pressure from armyworm or seedcorn maggot, legumes are the preferred cover crop rather than cereal grains. To ensure successful termination of a legume cover crop using mechanical methods, the legume must be rolled-crimped or mowed at 100% bloom or at early pod set. In the upper Midwest, this does not occur until approximately mid-June for hairy vetch, which is one month after typical organic corn planting dates. This results in significantly reduced yields of corn, or in some cases, failure of the crop to fully mature.

Legume cover crop breeding efforts could provide options to allow this system to be more successfully adapted to corn. While hairy vetch is currently the cover crop that has been most frequently tested under CCBRT management due to its ability to overwinter and establish sufficient biomass, other vining legume cover crops, such as Austrian winter pea, could provide more acceptable alternatives. While Austrian winter pea is more variable in its ability to survive upper Midwestern winters, new cultivars with improved cold-hardiness are becoming available. Combined with agronomic practices that enhance overwintering of Austrian winter pea, such as earlier planting dates, deeper planting depth, and sowing with a winterkilled nurse crop such as oat, it may become a more reliable alternative for organic farmers interested in adapting CCBRT to the corn phase of their rotation. Austrian winter pea can offer significant advantages over hairy vetch as a cover crop, including earlier flowering dates and more effective termination, leading to silage corn yields equivalent to those resulting from typical organic management.

In addition to further research and investments in cover crops for suitability for the CCBRT system, cultivar selection and breeding for cash crops adapted to CCBRT remains a component of the system where a dearth of information exists. The value of breeding crops for specific organic environments is increasingly recognized [38]. Similar to the diversity across organic environments imparted by different fertility inputs, pest management strategies, and crop/cover crop rotation, the integration of CCBRT creates yet another unique management aspect to organic crop farms. Soybean and corn cultivars that can withstand cooler soil temperatures, establish through the thick cover crop residue, and withstand a narrow row spacing could provide specific trait advantages to improve performance in the CCBRT system.

Further optimization of equipment adapted to CCBRT can also contribute to the optimization of the system and more consistent, improved results. Manufacturers such as Dawn Biologic in Illinois, USA [39] and Cross Slot®No-Tillage Systems in New Zealand [40] are experimenting with alternatives that may improve proper seed depth and spacing. Further research to optimize existing corn planters and no-till drills is also needed, to provide better recommendations as to the most effective coulters, closing wheels, and other equipment modifications.

Additionally, to more effectively motivate farmers and policymakers to integrate the technique into management and policy decisions, more research must be conducted to understand the long-term impacts of CCBRT on SOC, SOM, and soil microbial communities. While overall organic farming practices have also been shown to increase soil C concentrations [38], the impacts of organic CCBRT on soil C dynamics is less clear. Several European-based studies have estimated gains in soil C stocks with reduction of tillage in organic systems, but have not conducted these estimations in systems where tillage is reduced to the extent of CCBRT [41–44]. While it can be hypothesized that the CCBRT would similarly improve soil quality parameters, this has not yet been well-documented on long-term CCBRT fields under upper Midwestern production and soil conditions.

6. Conclusions

As organic systems continue to expand and mature in the US, organic management strategies to reduce production risk while providing continued ecosystem services will become even more critical to the continued growth and success of the industry. A decade of CCBRT research in the upper Midwestern US has demonstrated that CCBRT can provide a strong management tool for organic farmers aiming to improve their weed management practices while minimizing soil erosion risk, building soil organic matter, and incorporating further crop diversity into their rotations. Particularly in the face of climate change, where extreme weather events will occur with increasing frequency and the need for carbon mitigation tools becomes more imperative, CCBRT provides both management advantages and broader ecosystem services. While research continues to occur at land-grant universities, the continued integration of farmer experiences as adoption increases will provide refinement to the system to further reduce risk and allow for successful implementation of CCBRT over a range of environments and rotation strategies.

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