Cover Crop Effectiveness Varies in Cover Crop-Based Rotational Tillage Organic Soybean Systems Depending on Species and Environment

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Abstract: Organic farming relies heavily on tillage for weed management, however, intensive soil disturbance can have detrimental impacts on soil quality. Cover crop-based rotational tillage (CCBRT), a practice that reduces the need for tillage and cultivation through the creation of cover crop mulches, has emerged as an alternative weed management practice in organic cropping systems. In this study, CCBRT systems using cereal rye and triticale grain species are evaluated with organic soybean directly seeded into a rolled cover crop. Cover crop biomass, weed biomass, and soybean yields were evaluated to assess the effects of cereal rye and winter triticale cover crops on weed suppression and yields. From 2016 to 2018, trials were conducted at six locations in Wisconsin, USA, and Southern France. While cover crop biomass did not differ among the cereal grain species tested, the use of cereal rye as the cover crop resulted in higher soybean yields (2.7 t ha^{-1} vs. 2.2 t ha^{-1}) and greater weed suppression, both at soybean emergence (231 vs. 577 kg ha^{-1} of weed biomass) and just prior to soybean harvest (1178 vs. 1545 kg ha^{-1}). On four out of six sites, cover crop biomass was lower than the reported optimal (<8000 kg ha^{-1}) needed to suppress weeds throughout soybean season. Environmental conditions, in tandem with agronomic decisions (e.g., seeding dates, cultivar, planters, etc.), influenced the ability of the cover crop to suppress weeds regardless of the species used. In a changing climate, future research should focus on establishing flexible decision support tools based on multi-tactic cover crop management to ensure more consistent results with respect to cover crop growth, weed suppression, and crop yields.

Keywords: weed management; organic farming; mulch; weed dynamic; cereal grain cover crop; roller-crimper

1. Introduction

Worldwide, land under certified organic production reached 698 million hectares in 2017 [1]. Across the global organic land base, the production of organic soybean [*Glycine max* (L.) Merr.] is increasing, with 429,621 ha under production in 2017 [1]. With more than 39,996 ha of organic soybean grown in 2014, the United States is the third largest producer of organic soybean [1–3]. In recent years, the European market is also rapidly expanding, with 72,710 ha of organic soybean production in 2016 [1,4]. Within Europe, France leads organic soybean production with 24,615 ha.

Improved weed management and increased crop productivity have emerged as two main levers to facilitate the expansion of organic soybean acreage and meet the production demand [5,6]. As the prohibition of most synthetic substances is included in global organic regulatory frameworks, alternative

techniques have been developed to manage weeds, including mechanical cultivation, strategic crop rotation, and the use of cover crops [7–10]. For most organic farmers, soil tillage is necessary to manage weeds, prepare the seedbed, and incorporate organic inputs [11]. However, intensive soil disturbance may decrease soil quality (e.g., reducing organic matter, increasing soil erosion, etc.), thereby raising concerns on the sustainability of organic farming practices [12].

To maintain soil fertility, organic farmers are encouraged by the Food and Agriculture Organization of the United Nations (FAO) to reduce soil tillage, improve soil coverage and diversify crop rotation [13–15]. Among all the techniques developed to reduce tillage, organic cover crop-based rotational tillage systems (organic CCBRT) has emerged as a practice of great interest. These systems reduce tillage through the establishment of cash crops into high residue cover crops terminated with a roller-crimper [16–19]. The cover crop mulch remains on the soil surface until cash crop harvest, preventing weed emergence, and thus eliminating the need for mechanical weed management, maintaining soil quality while reducing labor and fuel consumption. In addition to creating a physical barrier which reduces weed emergence, an additional mechanism of weed suppression includes the competition of the cover crop with weeds for water, nutrients, and light [20,21]. Further, weed control may also be enhanced through allelopathic compounds released by the cover crop, which can inhibit weed germination [20,22–26].

Currently, reduced tillage practices implemented within conventional row crop systems are highly dependent on the use of chemical herbicides [17,27–29]. Growing concerns about the detrimental impacts of herbicides and the increasing occurrence of herbicide-resistant weeds have stimulated research interest for CCBRT in both organic and conventional production systems, especially in the United States where this technique has seen significant growth over the past decade [19,30,31]. The technique is less developed in Europe, but farmers' interest in preserving soil quality is increasing, as shown by a European survey conducted in 2012 on organic conservation practices [32].

Previous research has shown that effective weed control can be achieved through CCBRT until crop harvest if the cover crop biomass reaches from 8000 to 10,000 kg ha^{-1} according to conditions (e.g., climate, weed infestation, weed species) before termination [16,33]. Cover crop species selection also serves as a fundamental tool to (1) optimize cover crop biomass, (2) inhibit weed germination through the release of allelopathic compounds and (3) ensure adequate termination of the cover crop with a roller-crimper [34–36]

Some cereal grain cover crops perform well in CCBRT systems with soybean cash crops, including cereal rye (*Secale cereale* L.), triticale (*x Triticosecale* Wittmack), barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.)], and winter wheat (*Trticum vulgare* L.) [37,38]. Their main advantages over legume species are the high biomass production and consistent termination with a roller-crimper.

Among the cereal grain cover crops, cereal rye has consistently superior performance in the organic CCBRT system, producing high amounts of dry matter and reaching anthesis (Zadoks stage 69) [36,37], the stage of maturity necessary for mechanical termination, earlier than other cereals [19,21,39,40]. Cereal rye has also exhibited a high degree of allelopathy, inhibiting weed seed germination [41,42]. Incomplete mechanical termination of cereal rye in organic CCBRT may result in volunteer cereal rye plants in subsequent phases of the crop rotation, which results in contamination of following crops with rye grain, affecting both quality and yields of subsequent crops [18,40,43,44]. Thus, in recent years, triticale and barley, species with lesser propensity to produce volunteer plants, have been explored as alternative cover crops to rye. Additionally, the more prostrate growth habit and wider leaves characteristic of these species may provide greater light interception, improving early season weed control [39,45]. However, a dearth of references exists on the comparative performances of different cereal species in organic CCBRT systems.

While previous studies have demonstrated the ability of cereal rye cover crops to suppress weeds, the success of the CCBRT technique remains highly variable across years and location [18,46]. Investigation of the performance of organic CCBRT systems over a broad range of pedoclimatic conditions with the comparison of some cereal grain cover crops is needed to understand the reasons

for failures and achieve more consistent success. Alternative cereal grain species such as triticale could provide similar results than cereal rye and provide benefits for facing soil and climate condition to reach consistent cover crop performance. The objective of this study was to examine the performance of two cover crop species used in combination with soybean in an organic CCBRT system under different pedoclimatic conditions through a multi-site experiment over two years: (1) In the Upper-Midwestern USA and (2) Southeastern France. This study aimed (i) to determine which cover crop species leads to the highest soybean success rate and (ii) determine the drivers of variability in cover crop performance, weed control and soybean yields observed in different pedoclimatic conditions.

2. Materials and Methods

2.1. Site Description

The trials were conducted on certified organic land at two locations in 2017 and four in 2018, located in the upper Midwestern U.S. and in Southern France. The US sites are characterized by short growing season with high seasonal rainfall, cold winter conditions, and warm summer temperatures, as compared to the European sites which were defined by a more temperate climate, with consistent cool conditions and lower precipitation.

Site A is the University of Wisconsin Arlington Agricultural Research Station (UW-AARS) in Arlington, WI, USA. The four other locations are in Southern France Rhône-Alpes region, with site B in Drôme, site C in Northwestern Isère, site D in Ain and site E in Northeastern Isère. Soil types and climates are presented in Table 1. At Arlington (site A), fields have been certified organic since 2009 and were under alfalfa cover crop from 2014 through 2016. The organic CCBRT system trial was initiated in 2017 and relies on the common four-year rotation practiced in the upper Midwestern U.S., including, corn, soybean, fallow, and small grain [19]. In Southern France (sites B, C, D, and E), annual trials were implemented in the typical crop rotation practiced by farmers under organic grain system which is based on similar crops rotation as encountered in the upper Midwestern U.S. (i.e., winter wheat, corn, soybean, alfalfa). At sites B and E, reduced tillage was practiced throughout the prior 10 year period, while the historical management practices at C and D sites relied on traditional tillage. Sites B, C, and D have been certified organic for 13–27 years, while sites E has been managed organically for three years.

Table 1. Description of the six experimental sites (soil and climate conditions).

Site	Year	Previous Crop	Soil Type	Organic Matter (%)	pH	Climate (Location)	Irrigation System (Yes/No)
17-Arl. A1 18-Arl. A2	2017 2018	Alfalfa Corn	Plano silt loam	3.7	7.3	Humid continental climate, 889 mm, 9.45 °C (UWAARS, 43°18′N, 89°21″ E, 315 masl)	No
17-Frce B	2017	Winter wheat	Loamy sand	2.6	7.8	Mediterranean climate, 835 mm, 12.1 °C (45°00′40.2″N 4°59′07.1″E)	Yes
18-Frce C	2018	Winter wheat	Fine loam clay	4.9	8.4	Oceanic and temperate climate, 877 mm, 11.3 °C (45°40′51.3″N 5°32′13.9″E)	No
18-Frce D	2018	Alfalfa	Loamy sand	2.7	8.5	Semi-continental climate with Mediterranean influence, 785 mm, 11.5 °C (45°49′10.9″N 5°02′05.6″E)	yes
18-Frce E	2018	Winter wheat	Fine loam	1.6	7.5	Warm temperate climate, 797 mm, 11.5 °C (45°35′09.9″N 4°55′29.3″E)	No

2.2. Experimental Design and Crop Management

At each location, two cover crop species were compared (cereal rye and triticale) using a randomized complete block design with four replications. The detailed field operations are presented in Table 2. Site A (Arlington, WI, USA) was a 0.48 ha field with 67 m × 9 m sub-plots. The French sites (B, C, D and E) were 0.23 ha fields with 24 × 12 m sub-plots. Winter rye, ('*Aroostook*' (site A), '*Dukato*' (site C, D, E), '*Ovid*' (site B)) and winter triticale ('*NE426GT*' (site A), '*Vuka*' (site B, C, D, E)) were planted at the end of summer or early fall of 2016 and 2017 (Table 2). Different 3 m wide drills were

used depending on the location (site A-Model 750, John Deere, Moline, IL, site B and E-Sulky Master, site C-Saphir 7/400-DS 125, Lemken). On site D, the drill was a 4 m wide Vitasem 402 A, Pottinger. Planting depth was standardized at 2.5 cm.

Roller-crimpers of different widths, weight and manufacturers were used to terminate the cover crops (site A 4.6 m, 1360 kg, I and J Manufacturing, Gap, PA, sites B, C and E 3 m, 1400 kg, University of Lyon 1, Rhône-Alpes region, France, site D-6 m, 3300 kg, FACA, Sky Agriculture). Soybeans were planted and cover crops were terminated when the latter reached 50% to 100% anthesis (Zadoks growth stage 65–69) both years, thus resulting in different soybean planting dates depending on year.

Soybeans were planted with a 4.6 m wide conservation tillage planter in Wisconsin (site A) (Model 1750 Max Emerge Plus, Conservation Tillage, John Deere, Moline, IL), a 6 m wide no-till drill on site C and D (Easydrill W 6000, Sky Agriculture), a 3-m wide no-till drill on site E (Easydrill 3000 Fertisem, Sky Agriculture), and a 4 m wide planter on site B (Maxima 2 TI M, Kuhn) (see Table 2 for row spacing). Crimping and planting were performed the same day in two separate passes across the field, except for 18-Frce E site where both crimping and planting were performed as a one-pass operation.

2.3. Data Collection

Weather data for site A was obtained from a meteorological station located at UW-AARS (from 2016 to 14 November 2017) and the Michigan State University Enviroweather Service (from 15 November 2017 to 2018). In France, individual stations were used for each site: Valence-Chabeuil (site B), Bourgoin (site C), Lyon-Bron (site D) and Reventin (site E). Weather data was collected from the fall of 2016 to the fall of 2018.

Cover crop biomass (in kg of dry matter.ha^{-1}) was determined by collecting aboveground biomass in four randomized quadrats per plots before cover crop termination (quadrat size 0.5 m × 0.75 m in France, 0.5 m × 0.5 m in Wisconsin). The samples were dried at 80 °C until constant weight. Cover crop height was also recorded on 20 randomized plants per plots.

Weed biomass (in kg of dry matter.ha^{-1}) was determined by collecting aboveground biomass in three randomized 0.5 m × 0.75 m quadrats per plots centered on the row at two different dates: (i) Date 1 in the summer (July or August) and (ii) Date 2 in the fall (September) prior to soybean harvest. Samples were dried at 80 °C until constant weight. Weed species were identified on each plot of each site in the summer (Date 1) to document the dominant weed species.

Soybean stands were determined by counting emerged plants on three randomized four linear meters portions of the rows within three weeks after planting. Soybean aboveground biomass was estimated at the flowering stage (between R3 and R5 soybean stage) on three randomized two linear meters per plot. Soybean height was measured on 15 randomized soybean plant per plots at the mid-flowering stage (between R3 and R5 soybean stage). In France, to estimate soybean yields, soybean aboveground biomass and soybean grain weight were measured on two linear meters. Samples were replicated three times per plot or 12 times per cover crop species (cereal rye and triticale). At Arlington (site A), yields were measured using a 4.6 m wide combine (Gleaner, AGCO) in 2017 and a two-row plot combine in 2018.

Table 2. Field operations at the different experimental sites.

Sites	Primary Tillage	CC [1] Planting	CC Seeding Rate (kg ha^{-1})	CC Row Spacing (cm)	CC Rolling & Soybean Planting	Number of CC Growth Days	Soybean Seeding Rate (Seed ha^{-1})	Soybean Cultivar	Soybean Row Spacing (cm)
17-Arl. A1	16 August, 22 August, 2 September, 19 September, 2016	19 September (triticale), 26 September (rye) [2], 2016	201.75	19	26 May and 30 May (Rye)/8 June (Triticale), 2017	273 (rye)/62 (triticale)	555,986	Viking 0.1706	76.2
18-Arl. A2	29 September, 2 October, 2017	2 October, 2017	201.75	19	6 June (rye)/ 11 June (triticale), 2018	247 (rye)/252 (triticale)	555,986	Viking 0.1706	76.2
17-Frce B	9 July, 15 August, 15 September, 2016	23 September, 2016	200	16.5	16 May, 2017	235	605,000	ES Mentor	50
18-Frce C	15 July, 8 August, 21 August, 2017	22 August, 2017	200	12.5	29 May, 2018	280	535,000	Klaxon	50
18-Frce D	25 July, 10 August, 21 August, 24 August, 2017	25 August, 2017	200	12.5	18 May, 2018	266	600,000	ES Mentor	50
18-Frce E	18 July, 14 August, 25 August, 2017	29 August, 2017	200	16.5	25 May, 2018	269	535,000	ES Mentor	33

[1] Cover crop, [2] high amounts of precipitation during cover crop planting on 19 September prevented its completion on the same day. Wet conditions did not allow for the completion of cover crop planting until 26 September.

2.4. Statistical Analysis

Linear mixed models were used to evaluate the effect of rye and winter triticale on cover crop height and biomass, weed biomass (Date 1 and Date 2), soybean population, biomass at flowering and yield. "Cover crop species" was treated as a fixed effect. The six sites and eight plots per sites were treated as a random effect. The "site" factor refers to "location x year". The following model was used for analysis:

$$Y_{ijk} = X_i + A_j + B_k + C_{jk} + XE_{ijk}$$

where *X* is the fixed factor (cover crop species), *A* the first random effect (sites), *B* the second random effect (plots), *C* the interaction between both random effect factors, *XE* the error term, *i* a particular cover crop species, *j* a particular site (location × year) and k refer to a particular plot.

ANOVA per factor was also conducted for each site. Cover crop height, soybean height and yield met the assumptions for analysis of variance (ANOVA). Cover crop biomass, weed biomass at Date 1 and Date 2, as well as soybean density and biomass, were transformed as needed to meet the assumption for analysis of variance using square root transformation. We used the R software for every statistical analysis in R version 1.1.463 © RStudio, Inc, and more precisely the lme4 package for the linear mixed models [47]. Statistical significance of the results was evaluated at a *p*-value < 0.05 and treatment means were compared using Tukey's pairwise comparison.

3. Results

3.1. Climate

Rainfall accumulation during cover crop establishment was greater at all sites in the fall of 2016 compared to the fall 2017 (290 to 300 mm vs. less than 200 mm between September and November) (Figure 1). Both September and October were drier than average in southern France in 2017, while November and December were wetter. In April 2017 and May 2018, Arlington (site A), received more rain than average. The site received between 348.2 and 379.7 mm between April and June both in 2017 and in 2018 while the French sites only received between 173.4 and 216.4 mm over the same period. The greatest difference in rainfall accumulation between Arlington and the French sites was observed in the summer. While Arlington (site A) received 198.6 to 278.6 mm between July and August of 2017 and 2018 the French sites only received 72.9 to 129.7 mm over the same period (Figure 1).

In Arlington in 2017, monthly average temperatures were below 0 °C from November to April. The coldest months were December and January, with a minimum air temperature mean of −16.3 °C. In 2018, the temperature raised above 0 °C a month later than in 2017 (early May vs. early April) and the coldest months were January and February with monthly minimum air temperatures of −12.8 and −11.5 °C, respectively. At the French sites, both winters were milder than in Wisconsin and periods of freezing temperatures were rare. In 2017, at site B, January was the coldest month with −1.5 °C on average. The monthly average temperature was above 10 °C from March to the end of the growing season. In 2018, February was colder than December and January with one week of frost. Meteorological stations close to the C, D and E sites indicated a monthly minimum air temperature of −1.2 to −0.7 °C in February 2018 compared with 4.5 to 5.5 °C in January. Monthly average temperatures were above 10 °C at the French sites at the beginning of April 2018.
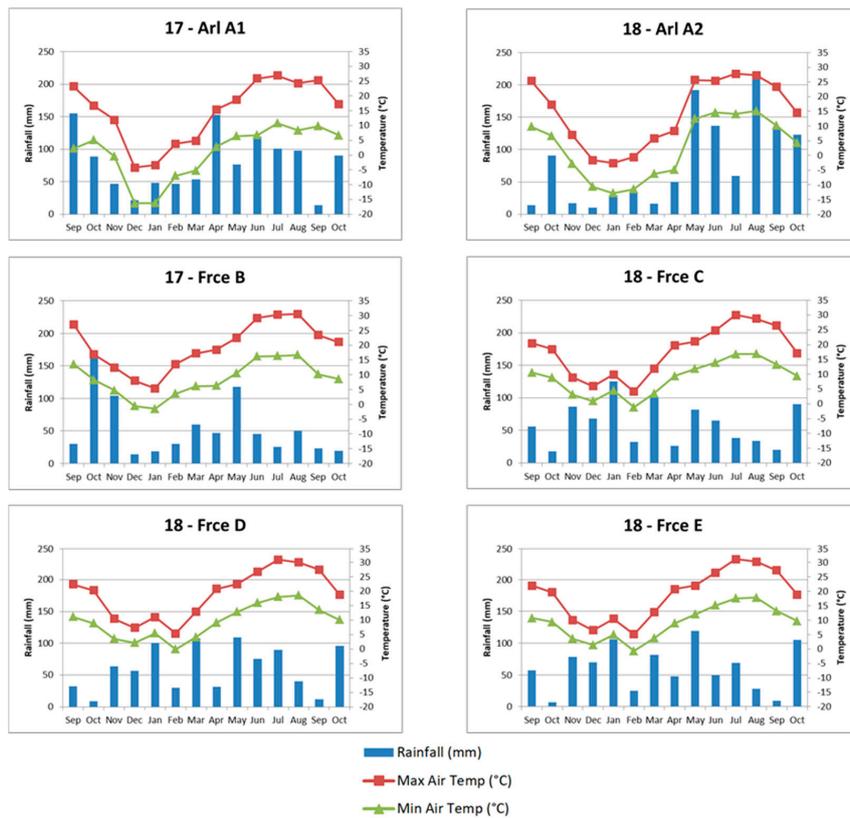
Figure 1. Monthly rainfall accumulation and average temperature for each of the six field locations over the 2016–2017 and 2017–2018 seasons.

3.2. Cover Crop Performance

Data from the six trials analyzed with linear mixed models did not show any significant difference in biomass production between cereal rye and triticale, with 6989 kg ha^{-1} and 7352 kg ha^{-1}, respectively (Figure 2). However, cereal rye grew significantly taller than triticale, 125 cm vs. 77 cm, respectively ($p < 0.001$).
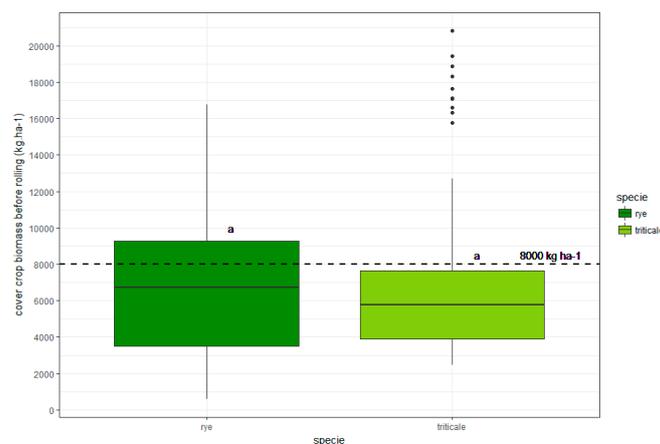
Figure 2. Mean weight of cereal rye and triticale biomass before cover crop rolling, averaged across all sites, 2017 and 2018. The linear mixed model did not indicate significant differences between cereal rye and triticale (*p > 0.05*, n = 144). Data presented in Figure 2 are means ± standard error. Each cover crop species (rye and triticale) followed by the same letter are not significantly different. The dotted line refers to a mean of the cover crop biomass values range reported in the scientific literature as a success factor to suppress weed until soybean harvest.

Cover crop biomass of both cereal rye and triticale was highly influenced by the pedoclimatic conditions (location x year) and varied from 2,963 kg ha^{-1} at the 18-Frce C site to 16,994 kg ha^{-1} at 17-Arl A1. Except for 18-Arl A2, the ANOVA performed per site showed a significant effect of cover crop species on cover crop biomass. However, the cover crop species producing the highest biomass differed between sites: Cereal rye for 17-Frce B and 18-Frce D sites and triticale for 17-Arl A1, 18-Frce C and 18-Frce E sites (Figure 3). In 2017, at Arlington, triticale produced significantly greater biomass than any other the site, resulting in the nine outlying data points seen in Figure 2.
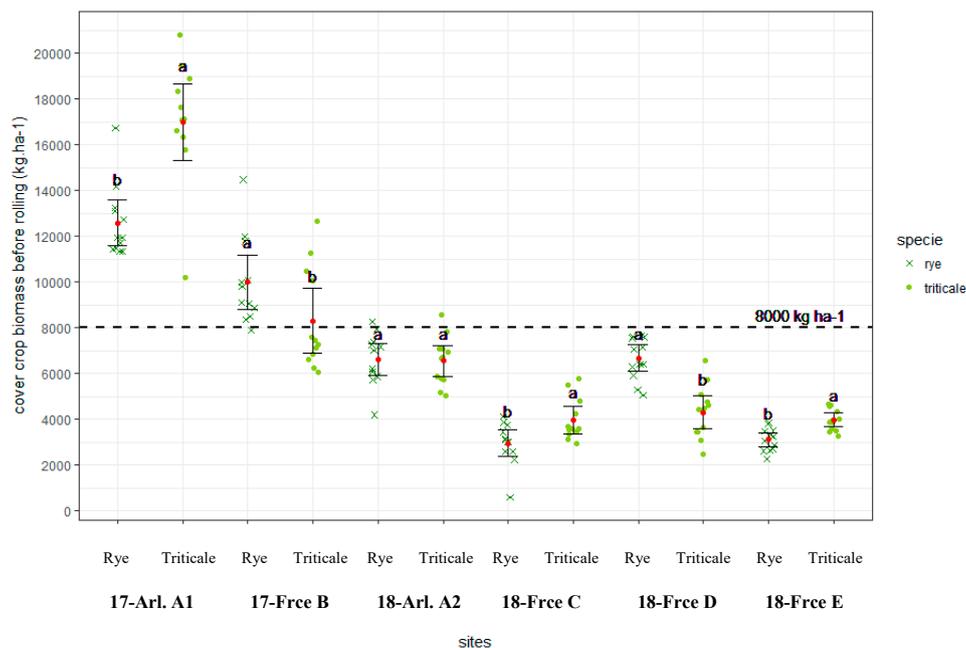

Figure 3. Cover crop biomass before termination per species and per site, 2017 and 2018. The letters represent the results of the ANOVAs per site ($p < 0.05$, $n = 24$). For each site, if the two species have the same letter their biomass is not significantly different. The dotted line refers to a mean of the cover crop biomass values range reported in the scientific literature as a success factor to suppress weed until soybean harvest.

3.3. Weed Biomass

In Wisconsin in 2018, the dominant weed species were Ladysthumb smartweed (*Polygonum persicaria* L.), lambsquarter (*Chenopodium album* L.), and foxtail (*Setaria pumila, Setaria viridis and Setaria faberi* L.). In France, the dominant weed species varied by location and year. At site B in 2017, common ragweed (*Ambrosia artemisiifolia* L.), heartsease (*Viola tricolor* L.) and Scarlet Pimpernel (*Anagallis arvensis*) dominated. In 2018, the weed population at site C was dominated by field bindweed (*Convolvulus arvensissuch* L.), all-seed (*Chenopodium polyspernum* L.) and round-leaved fluellin (*Kickxia spuria* L.) and at side D by yellow foxtail (*Setaria glauca* L.), switchgrass (*Panicum virgatum* L.) and persicaria (*Persicaria maculosa Gray* L.). Finally, in 2018 at site E, common ragweed was the main species along with annual bluegrass (*Poa annual* L.) and foxtail (*Setaria glauca* L.).

The linear mixed model determined that triticale provided poorer weed suppression compared to rye during the summer (Date 1), with 577 and 231 kg ha^{-1} of weed biomass for triticale and cereal rye, respectively (Table 3). A similar conclusion was shown in the fall (Date 2), with 1545 and 1178 kg ha^{-1} of weed biomass for triticale and rye, respectively. Weed dynamics between the summer and the fall did not differ significantly between rye and triticale. However, weed populations within the triticale cover crop tended to be higher than under cereal rye ($p = 0.09$) (Table 3). Indeed, data from the six trials indicated that the total weed biomass increased by an average of 945 kg ha^{-1} for the rye and 968 kg ha^{-1} for the triticale between Date 1 and Date 2.

Table 3. Summer and fall weed biomass from the two cover crop treatments over the six sites, 2017 and 2018. Weed biomass changes between the two dates, indicative of the degree of weed growth, are also reported.

Sites	Weed Biomass (kg ha^{-1}) Date 1 [1]		Weed Biomass (kg ha^{-1}) Date 2 [2]		Weed Biomass Change (kg ha^{-1}) Date 2–Date 1	
	Cereal Rye	Triticale	Cereal Rye	Triticale	Cereal Rye	Triticale
17-Arl. A1	83	148	287	274	204	127
18-Arl. A2	123	1214	55	869	−68	−345
17-Frce B	402	1119	319	857	−83	−262
18-Frce C	327	177	1245	1270	919	1093
18-Frce D	317	639	3479	4445	3163	3806
18-Frce E	134	163	1683	1554	1549	1391
Mean [3]	**231 a**	**577 b**	**1178 a**	**1545 b**	**947 a**	**968 a**
p-value [β]	<0.001		<0.001		0.09	
Significative Effect	***		***		.	

[1] Weed biomass was collected in July in France and in August at Arlington. [2] Weed biomass was collected in September. [3] Weed biomass mean from data of the six sites ($n = 6 \times 24$) (17-Arl. A1, 18-Arl. A2, 17-Frce B, 18-Frce C, 18-Frce D, 18 Frce E) are presented in bold in the table for each cover crop specie Cereal Rye and Triticale at the different dates of measurement (Date 1 and Date 2). [β] Linear mixed model, n = 144, Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1. Numbers in bold in the table followed by the different letters for Cereal Rye and Triticale within a similar date (Date 1, Date 2 or Date 2-Date 1) are significantly different.

The ANOVA per site showed that at the 18-Frce D site, the weed biomass was particularly high in the triticale plots with more than 4000 kg ha^{-1} (Table 3). Significant differences between triticale and cereal rye were also observed during the summer (Date 1) at the 18-Arl. site with 1214 kg ha^{-1} and 123 kg ha^{-1} of weed biomass, respectively. 18-Frce C is the only site where cereal rye resulted in poorer weed suppression compared to triticale. However, at that site, increased weed biomass between Date 1 and Date 2 in the triticale was observed as compared to rye (Table 3).

In France, except for site B where weed development was limited, an increase in weed biomass of more than 1000 kg ha^{-1} was observed between Date 1 and Date 2 for both cover crop species. At Arlington, weed biomass only increased by 204 kg ha^{-1} (cereal rye) and 127 kg ha^{-1} (triticale) between Date 1 and 2 in 2017 and decreased between the two measurements in 2018. Overall, the greatest increase in weed biomass between summer and fall was observed at 18-Frce C, D, and E (Table 3).

3.4. Soybean Performance

Using the linear mixed model, no differences were observed in soybean population between the two cover crop species, with an average of 309,020 plants ha^{-1} in the rye and 309,562 plants ha^{-1} in the triticale. At flowering, soybean biomass tended to be higher when planted into rye as compared to triticale, with 1,876 and 1,624 kg ha^{-1}, respectively (*p* = 0.07). Soybean height at flowering was also greater under rye cover crop (53 cm) compared to triticale (47 cm) (*p* < 0.01).

The linear mixed model indicated that the choice of cover crop species significantly affected soybean yields (Figure 4). Using cereal rye as opposed to triticale as a cover crop resulted in increased soybean yields of 0.1 to 1.3 t ha^{-1}. At the sites where triticale produced more biomass than rye, the yield gap between the two cover crop species was the lowest. At sites A1, C and E yields were only 0.2, 0.1 and 0.3 t ha^{-1} lower in the triticale (Table 4). The ANOVA per site also illustrated higher yields of soybeans grown with rye as compared to triticale, except for 18-Frce C and D where the variability within plots was high (*p* > 0.05) (Table 4). Independent of cover crop species, standard deviation varied from 0.8 to 0.9 t ha^{-1} at sites 18-Frce C, D, and E, it was 0.7 t ha^{-1} at 17-Arl. A1 and 18-Frce B and only 0.15 t ha−1 at 18-Arl. A2.
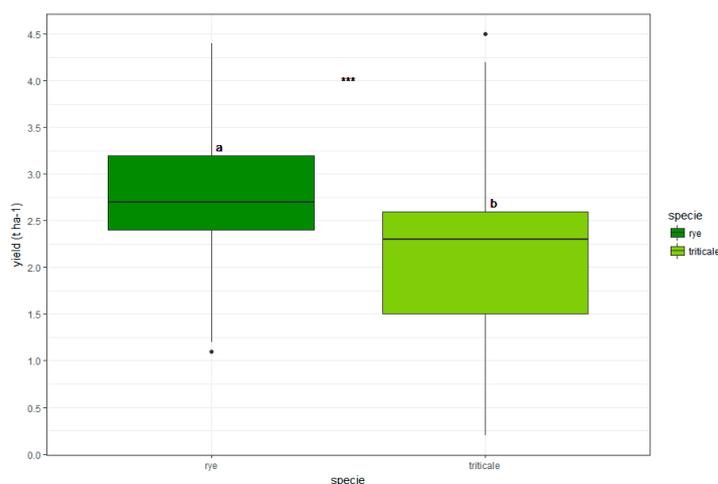
Figure 4. Soybean yields (t ha^{-1}) obtained from cereal rye and triticale cover crop treatments, averaged across all sites, 2017 and 2018, analyzed using linear mixed model ($p < 0.001$, $n = 144$). Boxplots followed by the same letters are not significantly different.

Table 4. Soybean yield (t ha^{-1}) averages per cover crop and per site, 2017 and 2018.

Sites	Soybean Yield (t ha^{-1})		Soybean Yield Losses on Triticale Cover Crop (t ha^{-1})
	Cereal Rye	Triticale	Cereal Rye-Triticale
17-Arl. A1	2.7 a	0.2 b	2.5
18-Arl. A2	3.5 a	2.2 b	1.3
17-Frce B	2.8 a	2.2 b	0.6
18-Frce C	2.7 a	2.6 a	0.1
18-Frce D	1.8 a	1.1 a	0.7
18-Frce E	2.6 a	2.3 b	0.3
Mean [1]	**2.7 a**	**2.2 b**	**0.5**
p-value (mean data) [β]	<0.001		-
Significative Effect	***		-

[β] Linear mixed model, $n = 144$, Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1. [1] Soybean yield mean from data of the six sites ($n = 6 \times 24$) (17-Arl. A1, 18-Arl. A2, 17-Frce B, 18-Frce C, 18-Frce D, 18 Frce E) are presented in bold for: Cereal Rye, Triticale and Cereal Rye-Triticale cover crop. Numbers followed by the same letters under the same line in the table are not significantly different.

4. Discussion

4.1. Cover Crop Biomass Production

On average across all sites, despite the difference in cover crop height prior to rolling (i.e., rye taller than triticale), the cover crop biomass did not differ between the two species. However, ANOVA per site determined a significant effect of species on biomass production under certain pedoclimatic conditions, with the most productive species varying between years and locations (Figure 3). Among the six trials, cereal rye biomass before rolling varied from 2936 kg ha^{-1} (18-Frce C) to 12,588 kg ha^{-1} (17-Arl. A1) and triticale biomass ranged from 3977 kg ha^{-1} (18-Frce E) to 16,994 kg ha^{-1} (17-Arl. A1). Environment (soil and climate) was thus identified as a factor explaining part of the variability observed in the cover crop biomass. This was consistent with other findings in the scientific literature [38,45,48,49]. Smith et al. [37] also found contrasting results between years and locations in North Carolina on sandy and loamy sand soil characterized by a warm humid subtropical climate. For example, a decrease in rainfall accumulation in 2009 was correlated with lower rye biomass (4450 kg ha^{-1}) compared to the previous year (10,854 kg ha^{-1}).

As discussed by Smith et al. [37], improved cover crop management including fertilization, planting date, seeding rate, species, and cultivar choice is fundamental to successful cover crop establishment and biomass production. This "management x environment" effect was observed at site A, with more than 10,000 kg ha^{-1} of biomass for both species in 2017 and less than 7000 kg ha^{-1} in 2018. The first year, the cover crop was planted after alfalfa and manure was applied before planting. The second year, planting occurred after corn harvested for silage and did not receive manure, with temperatures reaching above 0 °C a month later than the previous year. The shorter period of cover crop biomass production at 18-Arl. A2, combined with both lower precipitation during cover crop establishment in the fall of 2017 and lower nitrogen availability, resulted in lower biomass.

A similar impact of both environment and management was observed in France, where in 2018, cover crop biomass was lower than 4000 kg ha^{-1} for every species at every site except cereal rye on site D. The 2017–2018 growing season was characterized by below-average rainfall during cover crop establishment which affected cover crop emergence followed by above average rainfall in the winter which led to reduced tillering. With a fine loam clay soil type, the 18-Frce C was the most affected by the wet conditions. The water did not readily infiltrate through the soil, leading to cover crop stand losses (e.g., 2963 kg ha^{-1} of cereal rye biomass). A week of frost in February after mild January temperatures which had brought the cover crops out of dormancy also negatively impacted cover crop development in France in 2018. At site D, the earlier planting date (25 August), nitrogen credit from the preceding alfalfa crop, and mild fall temperatures (above 10 °C until November) led to rapid cover crop development before winter. The cover crop was thus at more sensitive stage than at other locations during the period of frost in February, which affected its biomass production potential. The significant difference in cover crop biomass between rye and triticale at site D in 2018 (6668 and 4314 kg ha^{-1}, respectively) was likely explained by the superior winter hardiness of rye compared to triticale (Figure 3).

Cover crop planting and termination timing have often been observed to play a key role in cover crop biomass production, explaining part of the variability between sites [50,51]. Mirsky et al. [33] discussed the increase of cover crop biomass production in May in mid-Atlantic region of US following earlier cover crop planting by comparing six planting dates across 10 day intervals under high annual precipitation condition evenly distributed (760–1012 mm) and silt loam soil. Delayed cover crop termination is critical to both improve cover crop termination and increase biomass production. Depending on specific annual conditions, cereal biomass can increase by 200 kg ha^{-1} per day after the stem elongation stage (i.e., after the 39 Zadok stage) [17]. In our study, planting dates varied from mid-August to early October and termination dates from mid-May to mid-June (Table 2).

One strategy to increase the resilience of the CCBRT may include the use of cover crop species mixtures. As suggested by Liebert et al. [39] in New York, mixing tall species such as cereal rye with species that are shorter with wider leaves such as triticale or barley can optimize early soil shading and hasten canopy closure. This strategy could improve cover crop establishment and early spring weed control as well as increase the probability of achieving adequate cover crop biomass at rolling under challenging conditions (e.g., soil type heterogeneity, drought, excess of water, etc.). The main drawback of using species mixtures is the lack of synchronization of anthesis of the different cultivars, which would need to be assessed for successful implementation of a roll-crimp system. Cover crop termination of cereal using a roller-crimper has been shown to be most effective when done between anthesis and early dough stage (Zadoks growth stage 61 to 85), with termination increasingly effective as the cereal matures to the soft dough stage [16,17,40,48,51].

The different cover crop cultivars used in the study particularly between the Upper Midwest and Southern France trials have to be considered as cultivar might impact the potential of cover crop biomass production, the cover crop sensitivity to cold temperatures and change climate as well as the cover crop flowering period [40,52]. In North Carolina, Wells et al. [40] observed higher cereal rye biomass (>9000 kg ha^{-1}) and greater cover crop control (100%) using earlier-flowering cultivar compared with late-flowering cultivar where cover crop biomass was inferior to 9000 kg ha^{-1} and

the cover crop control effectiveness was inferior to 65%. Thus, despite the cover crop biomass effect, ability to provide an adequate cover crop termination also might influence the weed pressure as well as soybean yield. To address the cultivar effect, interest in breed early-flowering fall rye is growing in North America to a specific adaptation for organic CCBRT as observed in Canada with the "CETAB + HÂTIF" cultivar [53,54].

4.2. Weed Biomass

As observed by Liebert and Ryan [55] and Ryan et al. [56] in humid continental climate and silt loam soil, results showed that when adequate biomass is produced prior to termination, the cover crop can significantly limit weed development. A sufficient amount of cover crop biomass remaining on the soil surface can reduce weed development by acting as a physical barrier, competing with weeds for nutrients, light, and water, and releasing allelopathic compounds [20,57,58]. Previous research has concluded that cover crop biomass should reach from 6000 to 10,000 kg ha^{-1} before termination to ensure adequate weed control until cash crop harvest, with more reliable control at biomass rates closer to 8000 kg ha^{-1} [17,18,37]. In our study, high levels of cover crop biomass (>8000 kg ha^{-1}) were reached at two sites: 17-Arl. A1 and 17-Frce B (Figure 3). At these sites, weed biomass increased by 127 to 204 kg ha^{-1} between Date 1 and Date 2, while at the other southern French sites, the weed biomass increased by more than 1000 kg ha^{-1} within the same timeframe. In Wisconsin, within the 18-Arl. A2 conditions, cover crop biomasses averaged 6615 and 6548 kg ha^{-1}, which although on the lower end of the anticipated acceptable range suppressed weed establishment throughout soybean season.

While species did not significantly differ in their biomass produced in our multi-site comparative study, cover crop species did differ in their weed suppression. Indeed, results showed that compared to triticale, cereal rye more effectively suppressed weeds through the entire soybean growing season. These results were consistent with previous organic CCBRT studies conducted in soybean or corn production systems. These studies also found that cereal rye used as a cover crop in CCBRT systems provided better weed control than other winter cereals or mixes of winter cereals and legume cover crops (e.g., winter wheat and winter pea, winter wheat, hairy vetch) [18,59,60]. In Iowa, located within the same cold temperate climate as Wisconsin, Delate et al. [18] observed lower weed pressure (broadleaf species) on silty clay loam soil with a cover crop mixture including cereal rye and hairy vetch compared to a mix of wheat and winter pea, with weed populations at the beginning of June of 2.2 plant m^{-2} and 6.5 plant m^{-2}, respectively. According to numerous researchers, the greater allelopathic effect of cereal rye may explain the greater weed control observed [61–63]. While few published studies directly address this phenomenon, within these systems where the cover crop remains on the soil surface, the release of allelopathic compounds could be delayed providing greater season-long effects [42].

Several studies have compared cereal rye and triticale as cover crops in organic CCBRT soybean production system. In conventional systems in Ontario, Canada, Moore et al. [60] indicated that cereal rye provided better control of redroot pigweed (*Amaranthus retroflexus* L.) than triticale and wheat. In organic systems, Silva [45] did not find any difference in weed biomass using cereal rye, triticale or barley as cover crop neither before cover crop termination nor 12 weeks after cover crop termination in Wisconsin in 2010 and 2011. These results contrast with our study, and the difference could be explained by the lower variability in cover crop biomass observed by Silva [45] in 2010 and 2011. In our study, the cover crop biomass was particularly low at three out of six sites (e.g., biomass less than 5000 kg ha^{-1}) while Silva [45] obtained more than 10,000 kg ha^{-1} of cereal rye, triticale and barley cover crop in 2010 and 2011 (with the exception of triticale in 2011 with 6380 kg ha^{-1}). When cover crop biomass is lower than 8000 kg ha^{-1}, according to Teasdale and Mohler [64] and Smith et al. [37] a difference of 1000 to 2000 kg ha^{-1} of rye biomass between cover crops may explain the success or failure of a CCBRT system. The broad range of pedoclimatic conditions encountered in our study did not allow for the confirmation of this hypothesis, but greater weed growth was observed between summer and fall when the cover crop biomass was less than 6000 kg ha^{-1}. At 18-Frce C, D and E sites,

where the cover crop biomass was less than 5000 kg ha^{-1}, weed biomass increased between Date 1 and Date 2 was high (918 to 3162 kg ha^{-1}). Conversely, at the 17-Arl. A1, 18-Arl. A2 and 17-Frce B sites where cover crop biomass was greater than 6000 kg ha^{-1} before rolling, the weed biomass remained stable or increased only slightly.

Despite of cover crop biomass and allelopathic effect, others factors related to the species characteristics also might influence weed management such as potential of tiller number production ensuring soil covering, leaf area, vegetative/reproductive ratio, decay dynamic of cover crop on soil surface (i.e., C/N ratio) and root growth [65]. These remain poorly documented in the literature, but recent promising paper promote the interest in species mixtures which can provide benefits for weed management and hasten canopy cover before cover crop rolling [39]. For instance, cereal rye combined with other species characterized by shorter height and wider leaves such as triticale or barley could increase light interception and shading.

4.3. Soybean Yield

Soybean emergence did not differ between cover crop species or between sites. On average, with a seeding rate between 535,000 and 605,000 seed ha^{-1}, resulting stands only reached 309,291 plant ha^{-1}. In Iowa, with the same seeding rate, Delate et al. [18] also observed poor emergence with a final stand count of 324,000 plant ha^{-1}. According to Wallace et al., in order to improve soybean emergence, major improvements to no-till planters must occur. To ensure appropriate seed-to-soil contact, no-till planters must slice through a thick cover crop mulch prior to opening and closing the planting furrow, as a poor seeding environment can result in poor soybean emergence and thereby affect soybean yields [21,66].

While not impacting soybean emergence, cover crop species treatments differed in their subsequent soybean yields. The cereal rye treatments resulted in significantly greater soybean yields as compared to using triticale, with 2.7 and 2.2 t ha^{-1}, respectively. In Pennsylvania, US, with humid continental climate and Southwest Germany, Europe, with moderately continental climate, Wallace et al. [21] and Weber et al. [66] also compared cereal rye with other cereal species as cover crops (i.e., barley (*Hordeum vulgare* L.), but did not observe any difference in soybean yield. To explain these results, the authors concluded that depending on the conditions, barley can produce adequate weed control due to quicker canopy closure and wider leaf blades compared to rye. Thus, combining rye with barley can result in similar weed control to the rye cover crop alone, thus leading to similar soybean yields. In our study, when the triticale produced equivalent or higher levels of biomass than rye, it provided equivalent weed suppression between Date 1 and Date 2 than rye, thereby limiting the yield loss observed on triticale compared with rye cover crop (17-Arl. A1, 17-Frce B, 18-Arl. A2).

Independent of the cover crop species, our results showed that the variability within plots (as measured by standard deviation) is increased in situations where the cover crop biomass is low (i.e., < 6000 kg ha^{-1}). The improved weed control provided by cover crop biomass in excess of 6000 kg ha^{-1} (i.e., 17-Arl. A1, 18-Arl. A2, and 17-Frce B) reduces water and nutrient competition between weeds and soybean plants, resulting in both more consistent and higher yields. However, cover crop biomass does not appear as the main factor explaining resultant soybean yields: While the average cover crop biomass did not differ among sites, the highest yields were obtained when planting soybean into rye. Additionally, soybean emergence does not seem to explain yield differences. Weed species and growth over the season, influenced by both (i) initial cover crop biomass before rolling and (ii) cover crop species, appeared as a driving factor impacting yields in our study. The allelopathic effect of rye likely influenced weed emergence as well, explaining the higher yields obtained compared to soybean planted into triticale.

5. Conclusions

This study illustrated the impact of the pedoclimatic condition on cover crop biomass produced using CCBRT systems, which subsequently impacted weed species and biomass dynamics throughout the soybean growing season. Despite location and year effect, choice of cover crop species remains a

fundamental decision for adequate weed suppression and sustainable soybean yields. Specifically, the results show that cereal rye remains the best candidate for successful organic CCBRT soybean production. The allelopathic effect of cereal rye likely suppresses weed seed germination to a greater degree than what is achieved by other annual cereal grain species. In addition, cereal rye is more winter hardy and reaches anthesis earlier than triticale, benefiting both biomass accumulation and timely planting with the roller-crimper. Our results provide further confirmation that sufficient cover crop biomass is crucial to suppress weeds throughout the cash crop production season. However, depending on location and year (e.g., dry, wet, degree and length of time below freezing), failures in cover crop establishment and/or poor development may be encountered with cereal rye and can lead to significant yield losses. On a farm-scale level, moving beyond evaluating cover crop decisions solely on agronomic performance, economic and practical considerations may impact farmer's choice. For example, cereal rye seed can be more expensive and difficult to access in some regions, such as southern France, as compared to other cereal grain species. With the high seeding rates needed in CCBRT systems, seed cost is a critical factor in the net profitability of the system. Mixing cereal rye with another high biomass cereal species such as triticale may allow for beneficial aspects of both species, including maximizing soil coverage among a variety of soil and climate conditions while reducing seed costs. In addition to the multi-tactic strategies previously highlighted to optimize cover crop biomass production (e.g., planting date, fertilization, irrigation, etc.), additional cover crop varieties and species mixes should be considered for further research (e.g., forage rye, forest rye, etc.). More broadly, in a changing climate, future CCBRT research should focus on flexible decision-support tools based on multi-tactic cover crop management to assist farmers in making the best decisions to ensure cover crop performance and weed management throughout the cash crop growing season.

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