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Organic Compared with Conventional Wheat Had Competitive Yields during the Early Years of Organic Production in the Northeast USA

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Abstract: Organic wheat production has increased significantly because of increased demand by consumers. We used the same variety to evaluate organic (seed treatment) and conventional wheat (no seed treatment) under no-till conditions in 2016 and 2018 with recommended (296 kernels/m^2 and 80 kg N/ha) and high inputs (420 kernels/m^2 and 56 + 56 kg N/ha) to identify the best organic management practices. Organic compared with conventional wheat with recommended inputs had ~13% lower yields in 2016 but ~7.5% higher yields with high inputs in 2018. Organic wheat emerged 1 to 1.5 days earlier, had 10 to 38% higher plant establishment rates, and had similar weed densities (<0.25 weeds/m^2) to high input conventional wheat, which received a fall herbicide. Organic compared with conventional wheat had lower grain N% (0.3 to 0.45% in 2016 and 0.17 to 0.27% in 2018). Organic compared with conventional wheat had mostly higher spike densities, especially with high inputs (~60 more spikes/m^2 in 2016 and ~130 more in 2018), probably because of better plant establishment, but mostly lower kernels/spike and kernel weight. Organic compared with conventional wheat had comparable yields, probably because of its competitiveness with weeds. We recommend that growers use recommended seeding and N rates on organic wheat because high seeding rates did not improve weed control, and high N rates were not economical.

Keywords: wheat; organic cropping system; weed densities; grain N%; yield components

1. Introduction

The number of wheat (*Triticum aestivum* L.) hectares in the USA has decreased significantly over the last 20 years [1]. In 2019, only ~18.5M hectares were planted in the USA, the lowest number since record-keeping began, and roughly half the hectares of maize or soybean [1]. Wheat, however, is the leading field crop in organic cropping systems in the USA, occupying ~136,200 hectares in 2016 compared to only 50,450 hectares of soybean and 105,675 hectares of maize [2]. A major reason for the prominence of wheat in organic field crop rotations is because wheat can disrupt pest cycles, especially weeds, in annual summer crops such as organic maize and organic soybean [3–5]. With an expected increase in organic wheat production in the Northeast USA, we initiated studies to identify the best management practices for growers who plan on transitioning to organic field crop production.

Many studies indicate that organic wheat yields are only 60 to 70% of conventional wheat yields [5–10]. In a study in Maryland, USA, however, organic compared with conventional wheat yields averaged only ~8% lower with a range of ~15% higher to 25% lower in 7 years of analyses [11]. In another study in central Italy, organic compared with conventional durum wheat yields averaged ~15% lower with a range from 5% higher to 32% lower in the 7-year study [12]. Organic compared with conventional wheat yields were much lower in years with high precipitation during the grain-filling stage because of increased weed infestation in organic wheat in the central Italy study.

Weed competition is a major constraint to organic wheat yield. Total weed ground cover prior to harvest was found to be 7× higher in organic compared with conventional wheat when averaged across 8 years in a study in Switzerland [13]. In another study in Switzerland, weed biomass in organic wheat was consistently higher under reduced tillage compared with moldboard plow tillage [14]. In the same study, higher weed biomass at harvest did not decrease organic wheat yields in a moldboard plowing tillage system, but higher weed biomass did decrease yields by ~15% in the reduced tillage system. In a study in western Canada on winter wheat, a doubling of seeding rates (600 seeds/m^2) reduced weed densities by 40% while lowering yields by only 4% [15]. In a winter wheat study in Australia, increasing crop densities from 100 to 200 plants/m^2 reduced weed densities by 50% and maximized yield [16]. In a western Canada study, weed biomass was 95 times higher, and grain yields were 40% lower in organic compared with conventional red spring wheat [17]. In another western Canada study, reduced tillage in organic spring wheat increased weed infestations, especially perennial weeds, but yield variability was explained more by soil nitrate levels than weed infestations [18].

Available soil N is another major constraint to organic wheat production [19]. In a 5-year study in Switzerland, organic wheat yielded only 64% of conventional wheat [9]. Furthermore, conventional wheat at 50% fertilization yielded more than organic wheat at full fertilization. Also, doubling the fertilizer rate in organic cropping systems did not improve organic wheat yields. Spikes/m^2 was the yield component most responsible for the yield differences among treatments. The authors concluded that there is a major need to improve the availability of organic nitrogen and the synchrony between the supply of N and the demand of N by the organic wheat crop [9]. In a study comparing N fertilizer and organic manure on winter wheat in northern Greece, organic wheat at an equivalent rate of fertilizer N yielded 21% lower than the fertilizer N treatment. Doubling the manure rate, however, increased spike density, resulting in similar yields between the 2× manure rate and the fertilizer N treatment [20]. The high manure rate, which had 2.15 g/kg of P, had the same N and P uptake and similar translocation rate of P to the grain as the fertilizer treatment [20]. In a study in India comparing four rates of composted manure with mineral N fertilizer during the transition period to organic production, wheat yielded 35 to 65% lower in the first transition year and 23 to 54% lower in the second transition year, mostly associated with lower spikes/m^2 and kernels/spike [21]. The authors concluded that the composted farmyard manure had slower release rates of N during the transition, but the buildup of organic N in organic fields will improve the mineralization rate over time as more manure is applied. A study in the Northeast USA, however, reported that topdressing organic wheat with Chilean nitrate increased organic wheat yields by 11% when compared with a manure only treatment and 6% higher than a topdressed dehydrated poultry manure treatment [22].

The number of organic field crop hectares in the USA has increased by ~11% annually since 2010 [2]. We evaluated organic and conventional wheat in a cropping system study to evaluate the maize (*Zea mays* L.)-soybean {*Glycine max* (L.) Merr.}-wheat/red clover (*Trifolium pretense* L.) rotation under recommended input management and high input management (high seeding rate, and high N rate). We previously reported the agronomic results of the organic and conventional maize comparison from this same study [23]. The objective of this manuscript was to determine if high seeding and N rates improved weed competitiveness and/or N uptake in organic wheat, thereby improving yields. The wheat comparison in this study is from the second transition year and the second year after organic wheat would have been certified and eligible for the organic premium, a time when profit margins are lowest for organic producers.

2. Materials and Methods

We initiated a 4-year cropping system study at a Cornell University research farm near Aurora, New York (42°44′ N, 76°40′ W) in 2015 to evaluate three sequences of the maize-soybean-wheat/red clover rotation under conventional and organic cropping systems. Three contiguous experimental fields (220 m × 40 m each) had a mixture of silt loam soils (fine-loamy, mixed, mesic, Glossoboric Hapludalfs; and fine-loamy, mixed, mesic Oxyaquic Hapludalfs). All three fields had tile drainage at 10 m spacing. The three fields had different cropping histories with three different previous crops in 2014, barley (*Hordeum vulgare*), maize, and soybean.

The experimental design was a split-split plot (four replications) with previous crops as whole plots, cropping systems (conventional and organic) as sub-plots, and management inputs (recommended and high inputs) as sub-sub plots. The entire 40 m lengths were planted to maize, soybean or winter wheat in each field, but plot length was shortened to 33 m to allow for 3.5 m borders on the north and south sides of the plots. Also, 3 m borders were inserted between sub-plots (cropping systems) to minimize spray drift or fertilizer movement from conventional into organic plots. Likewise, 3 m border plots were inserted between each sub-subplot to minimize border effects from each crop, which differed in height. Whole plot dimensions were 216 m wide and 33 m long, sub-plot dimensions were 27 m wide and 33 m long, and sub-subplot dimensions were 3 m wide and 33 m long. This manuscript will focus exclusively on wheat agronomics.

Winter wheat in central New York, USA is typically planted from mid-September through late October. The crop typically enters winter dormancy in late December (average high temperatures of 0 °C and average low temperatures of −10 °C in January and February), and breaks winter dormancy in mid to late March. Wheat is in the active tillering stage in April, the stem elongation phase in May, the anthesis stage in late May or early June, the grain filling stage in June and early July, and is harvested in mid-July.

Wheat followed soybean in the rotation in this study. Soybean was harvested in late September in 2015 and 2017 but on November 9 in 2016. Unfortunately, the soil was wet at soybean harvest, which prevented wheat being planted in 2016. Instead, we planted maize the following spring, which altered one of our intended maize-soybean-wheat/red clover sequences into a maize-soybean rotation. Consequently, wheat was planted in only 2 years (fall of 2015 and fall of 2017) instead of the intended 3 years. Conventional and organic wheat was no-tilled with a 3 m wide 1590 John Deere no-till drill (Molina, IL, USA) in 0.19 m rows the day after soybean harvest in both years. We originally did not intend to no-till organic wheat but decided to because there were very few visible weeds, especially winter perennial weeds.

We planted the same soft red winter wheat variety, 25R46, in conventional and organic wheat, but the conventional wheat seed was treated (mefenoxam, difenconazole, and sedaxane fungicide seed treatments plus thiamethoxam insecticide seed treatment) and the organic wheat seed was not. We applied 225 kg/ha of 10-20-20 (N-P-K analysis) as a starter fertilizer in conventional wheat. Unfortunately, we could only apply ~175 kg/ha of composted chicken manure (5-4-3, N-P-K analysis) through the planter as a starter fertilizer for organic wheat because of flow issues with the material through the grain drill. Conventional wheat received a top-dressing of 80 kg N/ha in late March (recommended input) or 56 kg N/ha in late March +56 kg N/ha in late April (high input) with ammonium nitrate (33-0-0). Organic wheat received a top-dressing of 80 kg N/ha in late March (recommended input) or 56 kg N/ha shortly after planting +56 kg N/ha in late April (high input) with composted chicken manure (Table 1). The composted manure was applied on the surface but not incorporated because of the no-till system. The company that makes the composted chicken manure claim that all of the N (5%) is available, but some organic growers and fellow researchers have expressed skepticism about that claim. Consequently, we assumed only 2.5% N was available and applied 2× the rate. The doubling of the manure rate could potentially cause a buildup of soil P concentrations, but soybean does not require fertilization in this environment so the manure would be applied to only 2 crops (maize and wheat) in the 3-year rotation. We also applied an herbicide (thifensulfuron + tribenuron) in the fall, and a fungicide (Prothioconazole + Tebuconazole) in the spring with a tractor mounted sprayer in high input conventional wheat. We frost-seeded red clover at ~11 kg/ha into all the wheat treatments in early March of 2016 and 2018 as a green manure crop to provide N to the subsequent maize crop.

Table 1. Planting rate, seed treatment, cultivar, tillage, starter fertilizer, N fertilizer, weed control, and plant disease control practices for wheat in conventional and organic cropping systems with two management inputs (recommended and high input) in 2016 and 2018 at a University Research Farm in central New York, USA.

Descriptor	Conventional		Organic	
	Recommended	High	Recommended	High
Planting rate (seeds/m^2)	296	420	296	420
Seed Treatment	Fungicide/insecticide		None	
Cultivar	Soft red winter wheat (P24R46)		Soft red winter wheat (P24R46)	
Tillage	No-Till		No-Till	
Starter Fertilizer (source)	225 kg/ha (10-20-20)		175 kg/ha composted chicken manure (5-4-3)	
N fertilizer (source)	80 kg N/ha (33-0-0)	56 + 56 kg N/ha (33-0-0)	80 kg N/ha (composted manure)	56 + 56 kg N/ha (composted manure)
Weed Control	None	Thifensulfuron + Tribenuron	None	None
Plant Disease Control	None	Prothioconazole + Tebuconazole	None	None

Wheat densities were taken 10–15 days after emergence by counting all wheat plants in six 1.52 m^2 regions along the 33-m harvest rows (8 center rows). Weed densities were also determined in wheat by counting all visible weeds along the 33 m length of the entire 3 m wide wheat sub-plot in early April, the beginning of the active tillering period in this environment. Predominant weed species, which not differ among the three fields or between cropping systems, included dandelion, (*Taraxacum officinale* F.H. Wigg); common mallow (*Malva neglecta* Wallr.); chickweed (*Stellaria media* (L.) Vill.); and common henbit (*Lamium amplexicaule* L.) Flag leaf disease ratings were taken during the grain-filling period but will not be reported because of negligible observed symptoms.

Yield components were determined a few days before harvest by hand-harvesting all the plants in a 1 m length of the eight harvest rows (1.52 m^2 area) every 10 m along the 33 m-length of the sub-subplot for a total sampling area of 4.56 m^2. Whole plants were air-dried in a greenhouse for a few days and weighed. Spikes were counted from each sample, and all kernels were hand-threshed and counted with a seed counter (Old Mill Co., Savage, MD, USA), which allowed us to determine kernels/spike. All kernels were then weighed and divided by kernel number to calculate individual kernel weight. All kernels were then ground, sampled, and brought to the lab to determine grain N concentrations by combustion (LECO CN628 Nitrogen Analyzer, LECO Corporation, St. Joseph, MI, USA).

The remaining three 10 m lengths in each sub-subplot were harvested with a 1.5 m wide small plot Almaco combine (Nevada, IA, USA) in early July of both years. An approximate 1000 g sample was collected from each sub-subplot to obtain two seed moisture estimates for each sub-sub-subplot. The data from the three 10-m harvest lengths were then pooled to estimate yield for each sub-subplot. Yields were adjusted to 13.5% moisture.

The Bartlett test ($p = 0.01$) indicated that variances were not homogeneous across years for yield, spike density, kernels/spike, and kernel weight. In addition, the cropping history differed between 2016 and 2018 with only 1 previous year of organic production in 2016 and 3 years in 2018. Consequently, we analyzed each year separately. Previous crop (three 2014 crops), cropping systems (conventional and organic), and management inputs (recommended and high) were considered fixed and replications random for statistical analyses of yield, weed densities, grain N%, and yield components for each year, using the REML function in the MIXED procedure of SAS (version 9.4; SAS Institute Inc., Cary, NC, USA). Fields with different previous crops (2014 crops) had weed density effects and kernel weight effects in 2016, but no yield and yield component effects or no interactions with cropping systems for any measured variables in either year of the study. Consequently, the data will be pooled across previous crops (the three contiguous fields) in both 2016 and 2018. Least-square means of the main effects (cropping system and management inputs) were computed, and means separations were performed on significant effects using Tukey's HSD (Studentized Range) test, with statistical significance set at $p < 0.05$. Differences among least-square means for cropping system interactions were calculated also using Tukey's HSD test. Two-way way interactions were detected for most variables, so the interaction comparisons will be presented. Simple correlations (Pearson) among all measurements within each year were calculated using PROC CORR in SAS with statistical significance set at $p < 0.05$.

3. Results

Weather conditions during the key growth stages of wheat were dry and cool for this environment with June being exceptionally dry in 2016 (Table 2). Precipitation from March through June totaled 197 mm in 2016 and 248 mm in 2018, 135 and 84 mm below average, respectively. Temperatures were below average from April through June in 2016, and much below average in March and April in 2018, which delayed the normal anthesis date by a few days in both years. Nevertheless, wheat was harvested on July 6 in 2016 and July 10 in 2018, 5–10 days before the normal harvest date, because dry conditions contributed to premature senescence.

Table 2. Monthly and total precipitation, and monthly average temperatures during the spring of 2016 and 2018 at a University Research Farm in central New York, USA.

	Precipitation			Average Temperature		
Month	**2016**	**2018 mm**	**30-yr.-avg.**	**2016**	**2018 °C**	**30-yr.-avg.**
March	48	82	64	3.7	−1.1	1.0
April	58	72	83	4.9	3.8	7.4
May	63	52	81	13.6	16.7	14.2
June	28	42	104	18.6	18.6	19.3
Total/Avg.	197	248	332	10.2	9.5	10.5

Wheat yield had a cropping system × input management interaction in both years (Table 3). Conventional compared with organic wheat in 2016 yielded ~13% higher with recommended inputs but similarly with high inputs because of an unexpected 9.5% yield decline in conventional wheat with high input management (Table 4). Lodging did not occur in 2016, so increased lodging, associated with higher seeding and N rates, was not a factor contributing to the yield decrease in conventional wheat with high input management. In 2018, organic wheat with high input management yielded ~7.5% higher than the other treatments. Yields averaged 37% higher in 2018 compared to 2016, probably because of 51 more mm of precipitation from March through June.

Organic compared with conventional wheat emerged ~1 to 1.5 days earlier in both years of the study (data not shown). Early plant establishment had a cropping system × input management interaction in both years (Table 3). Organic compared with conventional wheat had 10% to 20% greater early establishment in the autumn of 2015 and 28% to 38% greater early stand establishment in the autumn of 2017 in the recommended and high input treatments, respectively (Table 4). Early plant establishment did not correlate with yield in 2016 but had a positive correlation with yield in 2018 ($r = 0.39$, $p = 0.004$). Early plant establishment also correlated with spike density in 2016 ($r = 0.40$, $p = 0.005$) and in 2018 ($r = 0.74$, $p = < 0.0001$).

Table 3. *p*-Values for yield, early stand%, weed density, grain N% concentration, plants/m^2, spikes/plant, kernels (kern.)/spike, and kernel weight (Kwt.) in 2016 and 2018 on a research farm in central New York, USA.

Variable	Yield	Stand%	Weeds	Grain N%	Spikes/m^2	Kern./spike	Kwt.
				2016			
Previous Crop (PC)	0.74	0.61	0.04	0.53	0.34	0.50	0.01
Cropping System (CS)	0.17	0.01	0.001	<0.0001	0.24	0.02	0.04
PC × CS	0.18	0.55	0.09	0.49	0.89	0.13	0.66
Inputs (I)	0.001	0.04	0.01	0.002	0.14	0.34	0.22
PC × I	0.12	0.40	0.13	0.82	0.56	0.10	0.92
CS × I	0.001	0.001	0.0001	0.007	0.04	0.05	0.57
PC × CS × I	0.18	0.39	0.08	0.83	0.59	0.75	0.09
				2018			
Previous Crop (PC)	0.16	0.50	0.68	0.25	0.88	0.68	0.41
Cropping System (CS)	0.14	<0.0001	0.11	<0.0001	0.001	0.009	0.001
PC × CS	0.48	0.26	0.40	0.85	0.78	0.13	0.39
Inputs (I)	0.04	0.03	0.78	<0.0001	0.02	0.002	<0.0001
PC × I	0.58	0.41	0.71	0.34	0.70	0.94	0.12
CS × I	0.01	<0.0001	0.002	<0.0001	0.05	0.04	0.0001
PC × CS × I	0.40	0.54	0.37	0.48	0.53	0.85	0.09

Table 4. Grain yield, stand% (10–15 days after planting), weeds/m^2 (early spring), and grain N% of wheat in 2015–2016 and 2017–2018 under conventional and organic cropping systems with recommended and high input management at a University Research Farm in central New York, USA.

	Yield (kg/ha)		Stand%		Weeds/m^2		Grain N (%)	
Conventional	2016	2018	2016	2018	2016	2018	2016	2018
Recommended	4314 a [+]	5361 b	88 b	69 b	0.46 a	0.14 ab	1.95 b	1.89 b
High Input	3938 b	5315 b	78 c	60 c	0.01 b	0.02 b	2.11 a	2.09 a
Organic								
Recommended	3817 b	5345 b	98 a	97 a	0.05 b	0.10 b	1.65 c	1.72 c
High Input	3828 b	5752 a	98 a	98 a	0.04 b	0.23 a	1.66 c	1.82 b

[+] Treatment means within the same column followed by the same letter are not significantly different according to Tukey's HSD (Studentized Range) test at $p < 0.05$ level.

Weed density during the early tillering stage in early spring also had significant cropping system × management interactions in both years of the study (Table 3). Organic wheat had only ~0.05 weeds/m^2 in both treatments during the early tillering stage in 2016 (Table 4), similar to weed density in conventional wheat with high input management. In 2018, organic wheat had 0.10 weeds/m^2 with recommended inputs, similar to weed densities in conventional wheat with high inputs. Weed densities, which were quite low in both years, did not correlate with yield in either year of the study.

Grain N% also had a significant cropping system × input management interaction in both years of the study (Table 3). Organic compared with conventional wheat had ~0.30% lower grain N% with recommended inputs, but 0.45% lower grain N% with high inputs in 2016 (Table 4). In 2018, organic, compared with conventional wheat, had 0.17% lower grain N% with recommended inputs, but 0.27% lower grain N% with high inputs. Grain N% did not correlate with yield in 2016 ($p = 0.65$) nor in 2018 ($p = 0.11$).

Spike density had cropping system × input management interactions in both years of the study (Table 3). Organic wheat with high input management had ~60 more spikes/m^2 compared with the other treatments in 2016 (Table 5). In 2018, organic compared with conventional wheat had 48 more spikes/m^2 in the recommended input treatment, but 129 more spikes/m^2 in the high input treatment. Overall, wheat averaged 71 more spikes/m^2 in 2018 compared with 2016. Spike density correlated with yield in 2016 ($r = 0.41$, $p = 0.005$) and in 2018 ($r = 0.43$, $p = 0.003$).

Table 5. Spikes/m^2 at harvest, kernels/spike, and kernel weight of wheat in 2015–2016 and 2017–2018 under conventional and organic cropping systems at recommended and high input management at a University Research Farm in central New York, USA.

	Spikes/m^2		Kernels/Spike		Kernel Weight	
Treatment	**2016**	**2018**	**2016**	**2018**	**2016**	**2018**
Conventional						
Recommended	500 b	537 c	24.7 a	27.8 a	32.0 a	36.7 a
High Input	509 b	557 bc	24.2 ab	26.6 b	31.8 a	36.2 ab
Organic						
Recommended	503 b	585 b	23.0 b	26.9 b	31.3 b	35.7 b
High Input	563 a	686 a	21.1 c	23.9 c	30.7 b	33.5 c

+ Treatment means within the same column, followed by the same letter are not significantly different according to Tukey's HSD (Studentized Range) test at $p < 0.05$ level.

Kernels/spike had a cropping system × input management interaction in both years of the study (Table 3). Conventional compared with organic wheat had 1.7 more kernels/spike with recommended input management, but 3.1 more kernels/spike with high input management in 2016 (Table 5). In 2018, conventional compared with organic wheat had 0.9 more kernels/spike with recommended input management, but 2.7 more kernels/spike with high input management. Overall, wheat averaged ~3 more kernels/spike in 2018 compared with 2016. Kernels/spike had a positive correlation with yield in 2016 ($r = 0.59$, $p < 0.0001$), but did not correlate with yield in 2018 ($p = 0.29$).

Kernel weight had a cropping system effect, but no input management effect or no cropping system × input management interaction in 2016 (Table 3). When averaged across management inputs, conventional wheat had 0.9 mg greater kernel weight (Table 5). Kernel weight had a cropping system × input management interaction in 2018 (Table 3). Conventional compared with organic wheat had 1.0 mg greater kernel weight with recommended inputs, but 2.7 mg greater kernel weight with high inputs. Overall, kernel weight averaged ~4 mg greater in 2018 compared with 2016. Kernel weight did not correlate with yield in 2016 ($p = 0.11$) nor in 2018 ($p = 0.47$).

4. Discussion

The yield of organic compared with conventional wheat was more competitive in this study than reported in most other studies [5–10]. Our results showing a 13% decline in 2016 but similar or greater yields in 2018 agree more with another study in the Eastern USA where average organic wheat yields with moldboard plow tillage were only 8% lower than conventional wheat with reduced tillage or no-till [11]. Organic wheat typically has larger yield reductions compared with conventional wheat under reduced tillage systems [14,18], so the competitive organic wheat yields in our study under no-till conditions are thus more surprising. In our study, however, organic soybean was moldboard plowed the previous May or 4 months earlier so no-till organic wheat in this study was not in a no-till organic rotation but rather the sole crop that was no-tilled in the rotation.

Organic compared with conventional wheat had faster emergence rates and greater early plant establishment rates in both years of the study. The variety was the same in both cropping systems, as was the previous crop, tillage system, planting date, planter, planter depth, and planting rate. The only difference between the two systems at planting time was that conventional wheat received a fungicide/insecticide seed treatment, and organic wheat did not. Consequently, we surmise that the emergence and stand establishment differences must have been linked to the fungicide/insecticide seed treatment. We did not expect to see an improvement in stand establishment in conventional wheat with seed treatment because of the dry soil conditions before and after planting in both years of the study. On the other hand, we did not expect to see a delay in emergence and a lower emergence rate with the use of a fungicide/insecticide seed treatment. Wheat, however, typically compensates for low establishment rates by increasing tillering and subsequent spike number as well as increasing kernels/spike, resulting in similar grain yields, as long as establishment rates are not too low [24]. Consequently, establishment rates of conventional wheat may not have impacted yields in 2016 (establishment rates of 78 to 88%) but may have impacted yields in 2018 (establishment rates of only 60 to 69%).

Despite no-till conditions and applying no weed control practices, organic wheat during the tillering period had very low weed densities, similar to weed densities in conventional wheat with high input management, which received a fall herbicide application. The very low weed densities in organic wheat were unexpected because the use of reduced tillage in organic wheat increased weed densities greatly and reduced yields in other studies [14,18]. Perhaps cultivation in late July of organic soybean, the previous crop, destroyed early emerging winter perennial weeds, including the dominant weeds, dandelion and common mallow at this site. Weed densities, however, were also low in conventional wheat, which did not receive a fall herbicide, and followed conventional soybean, which received a single glyphosate application in late June. Consequently, a late July cultivation in organic soybean probably is not the major factor for the low weed densities in organic wheat.

Perennial weeds typically increase in organic cropping systems over time, [13,18] so it will be interesting to see if organic wheat, especially under no-till conditions, will remain competitive with weeds during the next cycle of the organic maize-soybean-wheat/red clover rotation. Wheat, however, has traditionally been very competitive with weeds in this environment, and some conventional wheat growers still do not use herbicides for weed control. The competitiveness of winter wheat with weeds in this environment provides it with a comparative advantage over other organic field crops such as organic maize and organic soybean, which require 4 to 5 cultivations for adequate weed control [23]. Organic growers in the Northeast USA probably do not need to focus too much attention on devising weed control practices for organic winter wheat during the first 4 years of organic management. An increase in seeding rate did not improve weed control in organic wheat so probably should not be used as a weed control tactic for organic wheat during the first 4 years of an organic rotation in the Northeast USA.

The lower grain N% in organic wheat compared to conventional wheat is undoubtedly associated with different N sources and/or timing of N applications in the two cropping systems. We assumed that only 50% of the N was available from the composted manure (2.5% N instead of the 5% N analysis) so we probably applied enough N. Instead, the composted manure applied to organic wheat with recommended inputs in late March of both years, the same rate and time that fertilizer N was applied to conventional wheat, may have mineralized only a limited amount of N during the cool April conditions in both years (2.5 to 3.6 °C below normal). The slow rate of mineralization of N of composted manure under the cool conditions would be exacerbated because of the surface application. A limited amount of mineralized N in April would decrease the amount of available soil N for N uptake during May, the stem elongation to anthesis stage when wheat takes up most of its N, leading to lower grain N% [25]. A split-application of composted manure in the fall shortly after planting and again in late April did not increase the grain N% of organic wheat with high compared to recommended inputs in 2016 but did increase grain N% by 0.1% and yield by 7% in 2018. The additional 32 kg N/ha in the high input organic treatment, however, was not economical in 2018 [23], and could increase soil P buildup so is not recommended in this environment.

The use of organic N sources on organic wheat appears challenging in this environment. The lower grain N% in organic compared with conventional wheat in both years of the study indicates that researchers should focus on devising N management strategies to provide adequate N to organic wheat during the stem elongation through anthesis stage in order to maximize grain yields. Chilean nitrate, an approved organic N source in the USA for 20% of the applied N on organic wheat, compared with composted manure top-dressed in the early spring, increased yield by 6% and crude protein by 0.06% [22]. The soft red winter wheat grown in this environment, however, is used for pastries and not for bread-making, so protein content is not of paramount importance to organic wheat growers in the Northeast USA. Also, Chilean nitrate is highly soluble, which could result in considerable nitrate losses during wet spring conditions.

The greater spike density in organic compared with conventional wheat with high input management in 2016 and in both management treatments in 2018 is probably associated with higher plant establishment rates, especially in the high input management treatment. In western Canada, increased spike density was found to be the major driver of organic wheat yields but not of conventional wheat yields [17]. Likewise, spikes/m^2 was the yield component most responsible for the yield of organic wheat in a Switzerland study [9]. In 2016, organic wheat with recommended and high inputs compared with conventional wheat with recommended inputs had similar spike densities (~500 spikes/m^2) but ~13% lower yields. In 2018, both conventional wheat management treatments and organic wheat with recommended inputs had yields within 46 kg/ha of each other, but spikes/m^2 ranged from 537 to 585 spikes/m^2. Spike density, which had significant positive correlations with yields in both years, was probably a contributing factor to wheat yields in this study, but probably not the major driver.

An increase in seeding rates and spike density typically results in a decrease in kernels/spike and/or kernel weight in wheat [26], commonly referred to as yield component compensation [27]. For example, organic wheat with high input compared to recommended input management had 101 more spikes/m^2, but 3.0 fewer kernels/spike and 2.4 mg lower kernel weight in 2018. Indeed, spike density had negative correlations with kernels/spike (r = −0.64, p = < 0.0001) and kernel weight (r = −0.60, $p < 0.0001$) in 2018. In 2016, however, spike density did not correlate with kernels/spike ($p = 0.72$) nor kernel weight ($p = 0.52$). Low N uptake can also reduce the number of kernels/spike and kernel weight in wheat [27]. Despite similar spike density between organic and conventional wheat with recommended inputs (503 to 500 spikes/m^2, respectively) in 2016, organic compared with conventional wheat with recommended inputs had 1.7 fewer kernels/spike, 0.7 mg lower kernel weight, and 0.3% lower grain N%. Grain N%, however, did not correlate with any yield components in 2016 so it is not clear if low N uptake was a contributing factor to the lower kernels/spike and kernel weight in organic wheat in 2016.

Spikes/m^2, kernels/spike, kernel weight, and wheat yields were much higher in 2018 compared to 2016 probably because of more spring precipitation in 2018. Total precipitation from March through June was 248 mm in 2018 compared with 197 mm in 2016. Undoubtedly, the additional 51 mm of precipitation resulted in more favorable conditions for kernel set/retention, grain filling, and grain yields in this environment where soils are relatively shallow (<0.75 m).

5. Conclusions

Organic compared with conventional wheat had competitive yields, but caution must be noted because the results are only from Year 2 and Year 4 of the study. In addition, conditions at planting and during the spring were dry in both years, which resulted in no visible plant diseases. If conditions had been wet after planting or during the spring, organic wheat yields might not have been as competitive because there are fewer organic compared with conventional fungicide products available for specific plant diseases. Nevertheless, the competitive wheat yields during the first 4 years of an organic cropping system should be encouraging to growers in the Northeast USA who are contemplating a transition to an organic cropping system. Competitive wheat yields during the first 4 years are critical because that is the period when organic growers are most vulnerable to economic losses [28].

Undoubtedly, the competitiveness of wheat with weeds in this environment is a major contributing factor for the competitive yields. Nitrogen uptake appears to be the major challenge for organic wheat production in this environment at least during the first 4 years in the organic rotation. Organic wheat with an additional 32 kg N/ha application did not increase yield in 2016 and provided only a ~7.5% yield increase in 2018, which was not economical [23]. Likewise, increased seeding rates did not improve weed control in this study. Consequently, we recommend that growers in the Northeast USA, who transition to an organic cropping system, plant wheat at the recommended seeding rate and apply the recommended N rate in the early spring during the first 4 years of organic production.

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