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Band sowing with hoeing in organic grains: II. Evidence of improved weed management in spring wheat, oats, field peas, and flax

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Abstract

The long-term success of weed management programs requires that all crops in a rotation receive satisfactory weed control. Band sowing with inter-band hoeing has been proposed as an innovative weed management strategy for grain crops. In the band-sowing system, crops are sown in a broadcast pattern within a band of some chosen width (here we selected 12.7 cm); weeds between bands are controlled with inter-band hoeing, with or without so-called "blind cultivation," for example, tine harrowing. Alteration of the crop spatial arrangement from typical single-line rows to a more evenly distributed pattern aims to enhance interspecific competition while reducing intraspecific competition. Field experiments, conducted in Maine in 2016 and 2017, compared band sowing with inter-band hoeing to the region's standard practice of planting in 16.5-cm rows and tine harrowing in four test crops: spring wheat (*Triticum aestivum* L. 'Glenn'), oat (*Avena sativa* L. 'Colt'), field pea (*Pisum sativum* L. 'Jetset'), and flax (*Linum usitatissimum* L. 'Prairie Thunder'). Band sowing improved weed control relative to the standard practice, especially in crops with greater competitive ability (wheat and oat). Despite improved weed control, in most cases, yields were unaffected by treatment. While band sowing with hoeing provided improved weed control in multiple crops, further study is warranted to optimize seeding rate, band width, and inter-band width to improve crop yields.

Introduction

Increased demand and attractive market prices for organic cereal grains have prompted farmers to increase production in the northeastern United States. However, weed management remains a challenging production problem. In grain crops, weeds reduce grain yield and quality, interfere with harvest, and may increase foliar disease (Jabran et al. 2017; Oerke 2006).

In organic farming, diverse crop rotation can be leveraged to increase crop yields while contributing to the management of weeds, insect pests, and diseases. Grain legumes such as field pea (*Pisum sativum* L.) are often included in rotations with cereals because of their nitrogen-fixing ability and associated low-input requirements (Stagnari et al. 2017). Field pea often improves the yield of subsequent cereal crops (Angus et al. 2015; Jensen et al. 2004; Stagnari et al. 2017). Flax (*Linum usitatissimum* L.), while not a legume, may likewise increase the yield of succeeding cereal crops (Angus et al. 2015). In the northeastern United States, there has been interest in growing oilseed flax as supplementary feed for dairy cows (Hafla et al. 2017); niche marketing opportunities may also exist for food and fiber (Singh et al. 2011). Additionally, both field pea and flax serve as break crops from diseases affecting cereals (Angus et al. 2015). The foremost challenge associated with organic production of field pea and flax, however, is also the management of weeds (R Kersbergen, personal communication). While diverse rotations have many benefits, poor or inconsistent weed management in any individual crops can negatively affect long-term performance due to the legacy effects of weed seed rain (Bagavathiannan and Norsworthy 2012; Brown and Gallandt 2018; Zentner and Campbell 1988).

In northern New England, USA, organic field pea, flax, and cereal crops are typically planted using a grain drill, in rows spaced 15- to 20-cm apart. Weed management relies on PRE and/or POST tine harrowing when weather and field conditions permit. Under ideal conditions, tine harrows can be extremely effective, resulting in high levels of weed control and improved crop yields. However, in less than ideal conditions, for example, larger weeds or wet soil, tine harrowing efficacy is low and variable (Gallandt et al. 2018). In fact, it is relatively common that tine harrowing benefits fail to overcome the direct negative effects on crop yield (Lundkvist 2009; Melander et al. 2005; Rasmussen 1991).

Ideally, sowing strategies, required seeding equipment, and physical weed control tools would be suitable for growing any grain crop, encouraging diversification without requiring additional capital investment. A promising alternative to planting with a typical grain drill and tine harrowing is band sowing with inter-band hoeing, a system also compatible with tine harrowing. Hoeing in cereals was first adopted by organic farmers in northern Europe who were experiencing intractable perennial weed problems. Band sowing offers potential improvements in both physical weed control and crop–weed competition. Instead of sowing seeds in single-line rows, shoe-type openers broadcast seed in 5- to 20-cm bands. Altering crop spatial arrangement from aggregated rows to a more uniform distribution within a band reduces intraspecific competition, increasing interspecific competition (Fischer and Miles 1973; Speelman 1975). Indeed, uniform sowing improved weed suppression and increased yields in spring wheat (*Triticum aestivum* L.) (Olsen et al. 2005; Weiner et al. 2001) and oat (*Avena sativa* L.) (Regnier and Bakelana 1995). The few studies that have compared band sowing with row planting have observed increased yields and weed control in cereal crops (Andersson 1986; Heege 1993; Huhtapalo 1986; Speelman 1975). Weeds in the inter-band zone are controlled by hoeing with sweeps. Compared with tine harrowing, sweeps offer greater weed control efficacy across a wider range of soil conditions, weed species, and weed sizes (Melander et al. 2003; Pullen and Cowell 1997).

Our objectives were to evaluate the effects of band sowing with inter-band hoeing on weed control and yield of several grain crops likely to be grown in rotation by farmers in northern New England, USA. Test crops included spring wheat, oat, field pea, and flax. We hypothesized that band sowing and hoeing would provide superior weed control and elevated yields when compared with the region's standard practice.

Materials and Methods

Site Characteristics, History, and Preparation

Field experiments were performed in 2016 and 2017 at the University of Maine Rogers Farm in Old Town, ME (44.93°N, 68.70°W). In both years, experiments were conducted on fields consisting of a Pushaw-Boothbay silt loam soil (fine-silty, mixed, semiactive, nonacid, frigid Aeric Epiaquepts; fine-silty, mixed, semiactive frigid Aquic Dystric Eutrudepts). Fields were managed uniformly before establishing the 2016 experiment; oats were planted on April 26, 2015, then mowed and incorporated; corn (*Zea mays* L.) was planted on July 31, 2015. The experiment was split into two fields in 2017, Blocks 1 and 2 were planted in Field J, and Blocks 3 and 4 were planted in Field G. In the year before the 2017 experiment, Field J was planted to field peas and was not treated with any herbicide; Field G was planted to potatoes (*Solanum tuberosum* L.) and was treated with metribuzin (Sencor 75 DF®, 3.3 g ai L^{-1}, Bayer CropScience, 100 Bayer Boulevard, Whippany, NJ, USA), *S*-metolachlor (Charger Max®, 7.2 g ai L^{-1}, WinField United, Arden Hills, MN, USA), and rimsulfuron (Matrix® SG, 1.5 g ai L^{-1}, DuPont, Wilmington, DE, USA). Fields used in the 2016 experiment were USDA certified organic, while fields used in 2017 were not certified; however, fields were managed organically in both experimental years.

Fertility was supplied by solid dairy manure based on soil test results to attain 73 kg ha^{-1} of plant-available nitrogen. Within 12 h before planting each crop, seedbeds were prepared using a Perfecta® Field Cultivator (Unverferth Manufacturing, Kalida, OH, USA).

Treatments

Test crops included hard red spring wheat ('Glenn'), oat ('Colt'), oilseed flax ('Prairie Thunder'), and field pea ('Jetset'). Field pea was inoculated with N-Dure® Pea/Vetch/Lentil (*Rhizobium leguminosarum* biovar *viceae*, Verdesian Life Sciences, Cary, NC, USA) before planting. Two treatments were implemented for each crop: our region's standard cropping practice (Standard) and band sowing with inter-band hoeing (Band+). Standard and Band+ treatments were planted at the same target density for each crop: wheat at 400 plants m^{-2}, oats at 325 plants m^{-2}, flax at 800 plants m^{-2}, and field peas at 100 plants m^{-2}. The Standard treatment was sown in 16.5-cm rows using a grain drill with double-disk openers (H & N Equipment, Colwich, KS, USA). The Band+ treatment was sown in 12.7-cm bands with 15.2 cm between planted crop bands (27.9-cm on-center spacing). Band-sown plots were planted using a Vicon air seeder (Kverneland Group, Klepp, Norway) with Dutch Openers (Dutch Industries, Pilot Butte, SK, Canada). Condiment mustard (*Sinapis alba* L. 'Ida Gold') was planted as a surrogate weed in all experimental plots. Mustard was selected as a surrogate weed due to its prior use in field studies (Kolb et al. 2010, 2012; Kolb and Gallandt 2012), and for its resemblance to wild cruciferous species affecting small grain crops in the northeastern United States, including wild radish (*Raphanus raphanistrum* L.) and wild mustard (*Sinapis arvensis* L.). Mustard was sown immediately after each crop at a rate of 65 seeds m^{-2} (Kolb et al. 2010) using a Brillion Sure Stand Grass Seeder (Landoll, Marysville, KS, USA). Tables 1 and 2 provide summaries of the field operations performed in 2016 and 2017, respectively.

Standard and Band+ treatments received POST tine harrowing when conditions permitted. Harrowing was performed with a Williams Tool System spring tine harrow (Market Farm Implement, Friedens, PA, USA) with 6-mm tines. The Band+ treatment also received inter-band hoeing using a Schmotzer cultivator (Maschinenfabrik Schmotzer GmbH, Windsheim, Germany), with 12.7-cm sweeps. Inter-band hoeing was either performed once or twice, depending upon field and weather conditions (Table 3).

Experimental Design

The experimental design was a split-plot randomized complete block design with four blocks. Plot dimensions were 1.8 by 7.6 m. Because growth rate and canopy architecture vary among crops tested, Standard and Band+ treatments of each crop were planted in adjacent plots within each block to ensure uniform competition and protect against edge effects. Therefore, the main-plot factor was crop type: wheat, oat, field pea, or flax; and the subplot factor was treatment: Standard or Band +. Guard plots planted to spring barley (*Hordeum vulgar* L. 'Newdale') were established throughout the experiment on either side of the paired plots.

Data Collection

To determine crop density (Table 4), stand counts were performed along three randomly placed 0.5-m lengths of row or band per plot before the implementation of POST tine harrowing or inter-band cultivation.

Before harvest, plant biomass from the intra- and interrow zones was cut at the height of 13 mm above the soil surface from three 0.25-m^{-2} quadrats per plot. Quadrat dimensions were selected to accommodate differences in crop configuration among treatments. Quadrat dimensions for the Standard treatment were 49.5 by 50.6 cm, and for Band+ were 55.9 by 44.7 cm. Standard quadrats were placed centered on a crop row, encompassing

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Table 1. Summary of dates and crop growth stages when field operations were performed in 2016.

	2016							
	Wheat		Oat		Field pea		Flax	
Field operation	Date	Stage[a]	Date	Stage[a]	Date	Stage[b]	Date	Stage[b]
Fertilize	May 16		May 16		May 16		May 16	
Sow crop and surrogate weed	May 18		May 18		May 18		May 18	
POST tine harrowing	June 9	13, 21	June 9	13, 22	June 9	15–17	June 9	13–15
First inter-band cultivation	June 9	13, 21	June 9	13, 22	June 9	15–17	June 9	13–15
Second inter-band cultivation	June 16	14, 22	June 16	14, 22	June 16	19	June 16	17–19
Peak biomass	July 29	85	July 27	85	July 26–27	79	July 27	85
Grain harvest	August 23		August 23		August 23		August 23–24	

[a]Wheat and oat growth stages are described using Zadoks et al. (1974) decimal code for cereals.
[b]Field pea and flax growth stages are described using Lancashire et al. (1991) BBCH decimal code.

Table 2. Summary of dates and crop growth stages when field operations were performed in 2017.

	2017							
	Wheat		Oat		Field pea		Flax	
Field operation	Date	Stage[a]	Date	Stage[a]	Date	Stage[b]	Date	Stage[b]
Fertilize	May 19		May 19		May 19		May 19	
Sow crop and surrogate weed	May 19		May 19		May 19		May 19	
POST tine harrowing	June 14	13, 21–23	June 8	12	June 14	14–16	June 22	19
First inter-band cultivation	June 14	13, 21–23	June 8	12	June 14	14–16	June 22	19
Second inter-band cultivation	June 29	15, 21–24	June 14	12, 21	–		–	
Peak biomass	July 30	87	July 31	87	August 1	88	August 8	85
Grain harvest	August 25		August 15		August 15		August 31	

[a]Wheat and oat growth stages are described using Zadoks et al. (1974) decimal code for cereals.
[b]Field pea and flax growth stages are described using Lancashire et al. (1991) BBCH decimal code.

Table 3. Cultivation events performed in 2016 and 2017.

			Cultivation events		
Year	Crop	Treatment	POST tine harrowing	First inter-band cultivation	Second inter-band cultivation
			no.		
2016	Wheat	Standard	1	–	–
		Band+	0	1	1
	Oat	Standard	1	–	–
		Band+	0	1	1
	Field pea	Standard	1	–	–
		Band+	0	1	1
	Flax	Standard	1	–	–
		Band+	0	1	1
2017	Wheat	Standard	1	–	–
		Band+	1[a]	1[a]	1
	Oat	Standard	1	–	–
		Band+	1[a]	1[a]	1
	Field pea	Standard	1	–	–
		Band+	1[a]	1[a]	0
	Flax	Standard	1	–	–
		Band+	1[a]	1[a]	0

[a]In the Maine 2017 site-year, the 1st inter-band cultivation event and POST tine harrowing were performed in sequence.

three rows, and Band+ quadrats were placed centered on an inter-band zone, encompassing two bands. Both the Standard and Band+ quadrats extended exactly halfway into adjacent interrow or inter-band zones. Quadrat sampling sites were randomly selected from the central area of each plot. Crop, surrogate weed, and ambient weed plant biomass were separated, and a census of surrogate weeds was performed. Ambient weeds were further divided into three categories based on field surveys of species relative density and frequency throughout the trial: most abundant weed species, second most abundant weed species, and all other ambient weeds. Separated plant matter was then dried for a minimum of 7 d at 49 C and weighed.

Wheat, oat, and field pea were harvested with a Wintersteiger Classic plot combine (Wintersteiger, Salt Lake City, UT, USA). To protect against edge effects, the outermost rows on either side of each plot were removed before harvest, in addition to approximately 0.5 m from the top and bottom of each plot. Final plot length and the number of rows or bands harvested were recorded

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Table 4. Crop population of wheat, oat, field pea, and flax in 2016 and 2017.

	Achieved crop density							
	2016				2017			
Treatment	Wheat	Oat	Field Pea	Flax	Wheat	Oat	Field Pea	Flax
	no. m^{-2}							
Standard	306	207	96	392	383	426	62	517
Band+	341	241	119	409	312	339	38	301
SE	20	10	10	29	14	18	7	31
Contrasts	P							
Band+ vs. Standard[a]	0.344	0.362	0.594	0.604	**0.018**	**0.004**	0.424	<**0.001**

[a]Bold font indicates statistically significant P-values.

Table 5. Total rainfall during the months of May to August in 2016 and 2017 compared with 30-yr means from 1988 to 2017.

	Total rainfall		
Month	2016	2017	30-yr mean
	mm		
May	77	124	91
June	65	68	100
July	119	47	76
August	62	43	74
Total	323	282	341

to inform crop yield per area (kg ha^{-1}) calculations. Flax was hand harvested from four randomly placed 0.25-m^{-2} quadrats and threshed by hand. Grain was cleaned using a Clipper Model 400 Office Tester and Cleaner (Seedburo Equipment, Des Plaines, IL, USA). Grain moisture of wheat, oat, and field pea crops was measured with a DICKEY-john GAC 2100 Agri (DICKEY-john, Auburn, IL, USA); flax moisture was determined using oven-drying methods outlined by the National Institute of Standards and Technology (Lee and Olson 2017). Yields were adjusted to a standard moisture content of 13.5%.

Analysis

JMP® v. 10.0.2 software (SAS Institute, Cary, NC, USA) was used to perform statistical analyses. Due to differences among the cultivation events performed in the Band+ treatment across experimental years (Tables 1–3) and significant treatment by year effects ($P \leq 0.05$), data from 2016 and 2017 were analyzed separately. Data were analyzed using a linear mixed model with crop, treatment, and crop*treatment as fixed variables, and block and block*crop as a random variables. Standard and Band+ treatment outcomes were compared for each crop using preplanned contrasts. Shapiro-Wilk's and Levene's tests were performed to confirm that data met the assumptions of a normal distribution and homogeneity of variance ($\alpha = 0.05$). If data did not comply with assumptions, square-root and $\log_{10}$ transformations were used. When treatment variables were compared, there were many instances where P-values fell between 0.05 and 0.10; after reviewing results, it was determined that a significance level of 0.10 would be used to characterize differences among groups.

Results and Discussion

Weather

Experiments were conducted in May through August, during which time total precipitation was 18 mm less than the 30-yr average in 2016, and 59 mm less in 2017 (Table 5) (NOAA 2017). In 2016, rainfall during May, June, and August was 23% below average; July, however, was quite wet, precipitation was 57% greater than average. The 2017 site-year started wet; we received 36% greater than average rainfall in May, whereas in the remaining months, rainfall was 37% below average.

Crop Density

In 2016, crop density did not differ between the Band+ and Standard treatments (Table 4). Wheat, oat, field pea, and flax populations were on average 81%, 69%, 108%, and 50% of their respective target densities.

In 2017, differences in crop populations occurred. Crop density in the Standard treatment was significantly greater than Band+ for wheat, oats, and flax, by 23%, 26%, and 72%, respectively (Table 4). Despite careful calibration of sowing depth and rate, the use of different planting equipment to sow Standard and Band + treatments is likely responsible for inconsistencies in crop emergence. On average, wheat, oat, field pea, and flax populations were 87%, 118%, 50%, and 51% of target densities, respectively. Possible crop density effects on treatment outcomes are discussed in the following sections.

Surrogate Weed Density

In 2016, band sowing with hoeing reduced surrogate weed density relative to the Standard treatment by 30% in wheat, 48% in oat, and 33% in field pea (Table 6). In 2017, the Band+ treatment reduced surrogate weed density in all crops tested, and averaged across crops, surrogate weed density was 39% less than in the Standard treatment (Table 7).

As weeds grow larger, they become more difficult to manage using physical methods of control (Pullen and Cowell 1997), including tine harrows (Baerveldt and Ascard 1999; Kurstjens et al. 2000; Lundkvist 2009) and sweeps (Johansson 1988; Melander et al. 2003). Band+ was designed to receive POST tine harrowing in addition to inter-band hoeing. In 2016, however, we refrained from harrowing so that inter-band hoeing could be performed when conditions were ideal and weeds were small. In 2017 hoeing and harrowing were performed on the same date, in sequence (Tables 2 and 3); it is likely that the improved performance of the Band+ treatment in 2017 is due in part to this change. Melander et al. (2001) found that combining interrow hoeing with tine harrowing improved efficacy on average by 30% when compared with hoeing alone.

Field peas were not hoed a second time in 2017 due to canopy closure between bands; hoeing would have caused considerable

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Table 6. Effect of crop sowing and weed management treatment (Standard and Band+) on end-of-season surrogate weed density, surrogate weed biomass, and ambient weed biomass in wheat, oat, field pea, and flax in 2016.

	2016											
	Surrogate weed density[a]				Surrogate weed biomass[a]				Ambient weed biomass[a]			
Treatment	Wheat	Oat	Field Pea	Flax	Wheat	Oat	Field Pea	Flax	Wheat	Oat	Field Pea	Flax
	——no. m^{-2}——				——g m^{-2}——				——g m^{-2}——			
Standard	27	33	33	21	28	60	83	74	70	72	177	254
Band+	19	17	22	25	16	15	45	106	40	58	106	209
SE	1	2	1	1	1	5	4	3	3	1	7	5
Contrasts	——P——											
Band+ vs. Standard[b]	**0.067**	**0.001**	**0.022**	0.374	0.251	**0.001**	**0.033**	0.132	**0.015**	0.296	**<0.001**	**0.070**

[a]Data were square-root transformed before analysis; back-transformed means are presented.
[b]Bold font indicates statistically significant P-values.

Table 7. Effect of crop sowing and weed management treatment (Standard and Band+) on end-of-season surrogate weed density, surrogate weed biomass, and ambient weed biomass in wheat, oat, field pea, and flax in 2017.

	2017											
	Surrogate weed density[a]				Surrogate weed biomass[b]				Ambient weed biomass[a]			
Treatment	Wheat	Oat	Field pea	Flax	Wheat	Oat	Field pea	Flax	Wheat	Oat	Field pea	Flax
	——no. m^{-2}——				——g m^{-2}——				——g m^{-2}——			
Standard	49	49	73	78	19.0	33	182	197	8.0	6.8	37	60
Band+	27	31	49	45	6.7	22	161	96	4.9	5.0	42	45
SE	2	2	2	3	1.3	1	2	10	0.3	0.2	1	2
Contrasts	——P——											
Band+ vs. Standard[c]	**<0.001**	**0.002**	**<0.001**	**<0.001**	**<0.001**	**0.083**	0.620	**0.005**	0.122	0.335	0.292	**0.012**

[a]Data were square-root transformed before analysis; back-transformed means are presented.
[b]Data were log10 transformed before analysis; back-transformed means are presented.
[c]Bold font indicates statistically significant P-values.

crop damage. Flax only received one hoeing in 2017 as well, because the first inter-band cultivation was delayed due to the crop's slow growth rate (Tables 2 and 3).

Surrogate and Ambient Weed Biomass

In 2016, the Band+ treatment decreased surrogate weed biomass (g m^{-2}) compared with the Standard treatment by 75% in oat and 46% in field pea; surrogate weed biomass was not affected by treatment in wheat or flax (Table 6). In 2017, the Band+ treatment reduced surrogate weed biomass relative to Standard by 65% in wheat, 33% in oat, and 51% in flax (Table 7).

Ambient weeds accounted for 70% and 23% of total weed biomass (surrogate and ambient weed biomass combined) in 2016 and 2017, respectively. Averaged across treatments, ambient weed biomass was composed of 32% redroot pigweed (*Amaranthus retroflexus* L.), 56% common lambsquarters (*Chenopodium album* L.), and 12% other ambient weeds in 2016; and 36% *C. album*, 8% yellow nutsedge (*Cyperus esculentus* L.), and 56% other in 2017 (data not shown).

In 2016, ambient weed biomass was reduced by band sowing in wheat, field pea, and flax by 43%, 40%, and 18%, respectively (Table 6). In 2017, the Band+ treatment reduced ambient weed biomass by 25% in flax (Table 7).

Surrogate weed density, surrogate weed biomass, and ambient weed biomass results support our hypothesis that band sowing in combination with inter-band hoeing would provide superior weed control to the region's standard practice. In the first year of the experiment, band sowing with hoeing reduced surrogate weed density and ambient weed biomass compared with the region's standard practice in three out of four crops, and surrogate weed biomass in two out of four crops (Table 6). In year 2 of the experiment, band sowing reduced surrogate weed density in all crops, surrogate weed biomass in three out of four crops, and ambient weed biomass in one of four crops (Table 7).

In the 2017 wheat crop, despite the Standard treatment having a crop density 23% greater than Band+ (Table 4), the average size of individual surrogate weeds (g $plant^{-1}$) was 38% smaller in the Band+ treatment (Table 8). Similarly, in the 2016 oat crop, the average size of surrogate weeds was 54% smaller in Band+. Thus, band sowing wheat and oat increased weed suppression compared with row sowing. Weiner et al. (2001) and Regnier and Bakelana (1995) found that increasing crop uniformity improved understory weed suppression due to an increased rate of canopy closure. In contrast, McCollough et al. (2020) reported an increase in the average weed size of band-sown spring barley compared with standard 16.5-cm row sowing.

Yield

Yields of wheat, oat, and field pea were on average 32% greater in 2016 than 2017, whereas flax yield was only 3% greater in 2017 (Table 9). Below-average rainfall in June, July, and August of 2017 likely contributed to reduced crop yields (Table 5).

Yield response to standard and band-sowing management strategies varied between years. Contrary to our hypothesis, in 2017, the Standard field pea yield was 55% greater than the Band+ treatment (Table 9). In 2016, there were no yield differences among treatments for any crop tested; and in 2017, no differences in yield were detected for wheat, oat, or flax, suggesting that crop response to competition from weeds did not differ between treatments.

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Table 8. Effect of crop sowing and weed management treatment (Standard and Band+) on the average biomass of individual surrogate weed plants in wheat, oat, field pea, and flax in 2016 and 2017.

	Average surrogate weed weight							
	2016[a]				2017[b]			
Treatment	Wheat	Oat	Field pea	Flax	Wheat	Oat	Field pea	Flax
	g plant^{-1}							
Standard	0.98	1.89	2.17	3.49	0.40	0.71	2.57	2.61
Band+	0.84	0.86	1.91	4.25	0.25	0.74	3.41	2.27
SE	0.01	0.11	0.03	0.08	0.02	0.01	0.09	0.04
Contrasts	P							
Band+ vs. Standard[c]	0.683	**0.014**	0.606	0.278	**0.017**	0.798	0.150	0.468

[a]Data were square-root transformed before analysis; back-transformed means are presented.
[b]Data were log_{10} transformed before analysis; back-transformed means are presented.
[c]Bold font indicates statistically significant P-values.

Table 9. Effect of crop sowing and weed management treatment (Standard and Band+) on yield of wheat, oat, field pea, and flax in 2016 and 2017.

	Crop yield							
	2016				2017			
Treatment	Wheat	Oat	Field pea	Flax	Wheat	Oat	Field pea	Flax
	kg ha^{-1}							
Standard	2,379	3,803	2,653	737	1,776	2,830	2,549	773
Band+	2,605	4,034	2,285	631	1,731	2,903	1,645	641
SE	86	83	425	39	95	106	255	162
Contrasts	P							
Band+ vs. Standard[a]	0.439	0.430	0.281	0.713	0.775	0.646	<**0.001**	0.409

[a]Bold font indicates statistically significant P-values.

Reduced 2017 field pea yield in Band+ is likely due in part to low crop density and poor timing of inter-band hoeing. Field pea population did not differ significantly between treatments in 2017; however, crop density in Band+ was 39% less than the Standard and 62% less than the target population (Table 4). In a weed-free crop, Stanley et al. (2018) found that hoeing reduced the yield of field pea; two and three interrow-hoeing events reduced yields by 14% to 31% and 19% to 31%, respectively. Stanley et al. (2018) also determined that field pea yields were negatively correlated with delayed interrow cultivation past BBCH growth stage 13.5 (Lancashire et al. 1991). We performed inter-band hoeing twice in 2016, when the crop was between growth stages 15 and 17, and again at stage 19 (Tables 1 and 3). In 2017, inter-band hoeing was performed once, when the crop was between growth stages 14 and 16 (Tables 2 and 3). To improve performance in field pea, inter-band cultivation should be performed once, 1 to 2 wk after crop emergence (Harker et al. 2001) when the crop is at BBCH growth stage 13 or 14 (Stanley et al. 2018).

In summary, all crops responded well to band sowing with hoeing; however, the response of oats and wheat was slightly more positive than that of field pea and flax. Cereal crops, including wheat and oats, are considered highly competitive (van Heemst 1985). According to Blackshaw et al. (2002), the competitive ability of our test crops would have the following rank order: oat > wheat > field pea > flax. In rank order, the average individual biomass of surrogate weeds across treatments was: wheat < oat < field pea < flax in 2016 and wheat < oat < field pea < flax in 2017 (Table 8). Reduction in weed biomass both reduces crop yield loss and weed seed rain, thus contributing to improved long-term weed management. Because band sowing relies on crop–weed competition for the successful suppression of weeds in the intra-band zone, cereal crops are likely best suited for band sowing. However, in our related work in spring barley, band sowing with hoeing effects on weed density, biomass, and crop yield were inconsistent (McCollough et al. 2020). It is important to note that our focus was on summer annual weeds. Crops with differing life cycles can improve the weed suppressive effects of crop rotation (Smith 2006); therefore, winter grains should be included in future research.

Overall, results from this study indicate that band sowing with inter-band hoeing is a promising weed management strategy for growing multiple grain crops. While band sowing improved weed control, yields were not consistently improved; an increase in yield was only observed for oat in one year. It is important to note that for each crop, a single seeding rate, band width, and inter-band width were tested. Before recommending band sowing to organic grain growers in northern New England, USA, we suggest that research be performed to evaluate the effects and interactions of these variables to optimize weed suppression and yield outcomes.

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