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Weed growth and crop performance following hairy vetch, rye, and wheat cover crops in a cool semiarid region

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Abstract Tillage is used to control weeds but can degrade soil quality. Our objective was to determine if tillage could be replaced by killed cover crop mulch for weed control when growing organic grain crops. An attempt was made to kill winter cereal and hairy vetch cover crops using a roller-crimper, wide-sweep blade plow, and disk (control) and then followed with warm-season buckwheat, dry bean, and maize grain crops during three growing seasons in southwestern North Dakota, USA. Aboveground weed production was greater in rolled-crimped hairy vetch than in rolled-crimped and disked rye plots. Maize failed to produce grain in any season, while buckwheat and dry bean produced harvestable grain following undercut or rolled-crimped cover crops in only one season. Even then, grain yield averaged only 37 kg ha^{-1} across cover crop and grain crop treatments in rolled-crimped plots, compared with 255 kg ha^{-1} in undercut plots and 487 kg ha^{-1} in disked plots. Yield likely would have been higher in tilled plots but tillage was imposed within 13 days of rolling-crimping, which required cover crops to reach advanced growth stages for effective termination. Rolled-crimped rye mulch can suppress weeds, but soil water deficits following cover crops and the delay needed for consistent termination may prevent timely seeding and successful grain crop production in single-season cover crop/grain crop relay systems in semiarid upper-latitude environments. Preliminary research indicates potential for use of rolled-crimped cover crop mulch for weed suppression in multi-year cover crop/grain crop relay systems in these regions, though additional research is needed which demonstrates commercial viability of this 2-year cropping strategy.

Keywords Cover crops · *Secale cereal* · *Vicia villosa* · Tillage · Conservation tillage

Introduction

Tillage is used in most integrated weed management programs to provide the level of control needed for successful organic crop production. Tillage can enhance weed control even in crop production systems where synthetic herbicides are used; downy brome (*Bromus tectorum* L.) populations were decreased 97 % when long-term (>20 years) no- or zero-till plots were plowed and then seeded with winter wheat (*Triticum aestivum* L. emend. Thell.) compared with seeding winter wheat in undisturbed zero-till plots in western Nebraska, USA (Kettler et al. 2000). The deleterious effects on surface soil quality that can result from a single tillage event also were demonstrated in that study, with organic carbon content 20 % less at the 0- to 7.5-cm soil depth 5 years after plowing in disturbed compared with undisturbed

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zero-till plots. Similarly, a single moldboard plowing of uncultivated grassland decreased soil aggregates at the 0- to 20-cm soil depth to sizes comparable to those in neighboring fields cultivated for over 50 years in the Midwestern Corn Belt in the USA (Grandy et al. 2006). Arbuscular mycorrhizae populations were reduced by almost 50 % at the 0- to 5-cm soil depth by one-time moldboard plowing in a separate study (Wortmann et al. 2008).

The negative impact that tillage can have on soil quality has stimulated interest in reducing tillage intensity and frequency in cropping systems managed organically. Peigné et al. (2007) concluded that replacement of intensive tillage with conservation tillage practices on organic farms should result in soil quality benefits similar to those following adoption in systems where synthetics fertilizers and pesticides are used, including increased microbial activity and carbon sequestration at shallow depths, reduced runoff and leaching of nutrients, and less fuel use and erosion. European researchers have focused on decreases in soil depth disturbance and replacement of inversion with noninversion practices to reduce tillage in cropping systems managed organically (Mäder and Berner 2012). In North America, some researchers have attempted to eliminate tillage completely when growing certain market crops organically, relying on vegetative mulch produced by killed cover crops for weed suppression (Carr et al. 2012b).

Previous research explored various implements and crop species that optimized weed suppression provided by killed cover crop mulch in the midwest (Creamer et al. 1995) and southeast USA (Creamer and Dabney 2002). Ashford and Reeves (2003) demonstrated that cover crops could be killed mechanically with little or no soil disturbance using blunt blades welded onto a roller to crimp plants and hasten termination. Subsequent research in the southeast USA focused on improving roller-crimper design to enhance killing effectiveness on cover crops and to improve operator comfort when using the implement (Kornecki et al. 2009).

Recent success with using rolled-crimped hairy vetch (*Vicia villosa* Roth) for weed suppression when growing maize (*Zea mays* L.), and rolled-crimped winter rye (*Secale cereale* L.) mulch when growing soybean (*Glycine max* [L.] Merr.), have been reported in systems managed organically in the US mid-Atlantic region (Moyer 2011). More consistent success has occurred with soybean than maize in these systems because of greater biomass production and persistence of rye compared with hairy vetch mulch, along with the ability of soybean to fix nitrogen biologically and compensate for reduced plant stands resulting from insect damage (Mirsky et al. 2012). Excellent weed control was provided to soybean when over 9,000 kg ha^{-1} of vegetative mulch was produced by rolled-crimped rye at two sites, and at one of two sites when between 7,000 and 9,000 kg ha^{-1} was produced in the southeast USA (Reberg-Horton et al. 2012). Differences in grain yield were not detected between plots where soybean was seeded into rolled-crimped rye and weed-free plots at those three sites, while yields were significantly less at two sites where less than 7,000 kg ha^{-1} of rolled-crimped rye residue was produced. These results confirmed previous research indicating that amounts of vegetative mulch produced by cover crops need to exceed 5,000 to 6,000 kg ha^{-1} to suppress annual grass species by 90 % and as much as 12,000 kg ha^{-1} to reduce densities of broadleaf weed species (Teasdale 1996). Both Mirsky et al. (2012) and Reberg-Horton et al. (2012) noted the ineffectiveness of cover crop mulch in suppressing growth of established perennial weeds.

Efforts to replace tillage with rolled-crimped cover crop mulch for weed suppression have not been successful consistently in central and western North America. Weeds were suppressed and crop yield was comparable when tomato (*Lycopersicon esculentum* Mill.) was transplanted into rolled-crimped rye/hairy vetch cover crop compared with tilled control plots in the midwest USA (Delate et al. 2012). However, lower yields resulted when soybean and particularly maize were seeded into rolled-crimped rather than tilled cover crops at that same location. Lack of plant-available water following cover crop termination, weed competition, regrowth of cover crops not killed by rolling-crimping, and plant-available nitrogen deficiency were suggested as explaining the low relative yields of zero-till maize, which were only 8 to 58 % of the yields in tilled control plots, depending on the year. Similarly, lack of nitrogen contributed to yield depression of wheat following pea (*Pisum sativum* L.) and pea plus oat (*Avena sativa* L.) cover crops that were killed by rolling-crimping compared with tilling in Manitoba, Canada (Vaisman et al. 2011). Yield reductions greater than 80 % occurred when cotton (*Gossypium barbadense* L.) and other crops were grown in rolled-crimped cover crop mulch compared with standard practices in California (Luna et al. 2012). Conversely, weeds were controlled and yield depressed only 20 % when pumpkin (*Curcurbita* spp.) was grown following rolled-crimped cover crops in the Pacific Northwest (Luna et al. 2012).

Weed growth has been suppressed by cover crop mulch in the semiarid prairie region of North America. Shirtliffe and Johnson (2012) reported that killing pea and faba bean (*Vicia faba* L.) cover crops by rolling-crimping or by mowing resulted in less weed biomass than killing cover crops by disking when crops were at early flowering growth stages in Saskatchewan, Canada. No difference in weed biomass was detected between termination methods when delayed until later growth stages of cover crops. Wheat grain yield was compared across termination methods but only after all plots were tilled in the Canadian study, preventing comparisons between grain yield under zero-till and clean-till systems. Weed dry matter (DM) production averaged 97 % more in 2 of 3 years when cover crops were terminated by rolling-crimping compared with disking in North Dakota (Carr et al. 2012a). However, cover crop selection impacted weed biomass production across termination methods dramatically, ranging from only 75 to 640 kg ha^{-1} for winter rye and from 584 to 2,436 kg ha^{-1} for hairy vetch, depending on the year.

Comparisons of grain yield for crops grown after killing cover crops could not be reported in the review by Carr et al. (2012a) nor could the interaction of cover crop selection and termination method on cover crop and weed DM production be described. Most importantly, impact of killed cover crop mulch on weeds in subsequent market crops could not be discussed in the review by Carr et al. (2012a). The two objectives of this research were to determine if: (1) weed growth was suppressed by killed cover crop mulch when grain crops were grown, and (2) if grain crops could be grown successfully when following cover crops killed by rolling-crimping in a single growing season. This manuscript describes results of the 4-year study.

Materials and methods

A study was conducted during 2007–2008, 2008–2009, and 2009–2010 growing seasons at Dickinson, North Dakota (46.895 latitude, −102.813 longitude, 779 m elevation) on sandy loam soils in fields transitioning to certified organic production in 2011. Five cover crop treatments were included: common hairy vetch, "Dacold" winter rye, "Seward" winter wheat, and mixtures of hairy vetch plus winter rye and hairy vetch plus winter wheat. "Tilney" mustard (*Sinapis alba* L.), "George" black medic (*Medicago lupulina* L.), and common forage turnip (*Brassica rapa* L.) were included in the hairy vetch plus winter rye mixture during the 2007–2008 field experiment but not thereafter because they failed to establish. Cover crop treatments were established using certified organic seed whenever possible in late-Sep to mid-Oct each year, depending on growing conditions. Treatments were established in fields that were fallowed for at least 30 days prior to seeding cover crop treatments. Crops grown prior to establishing the field experiments along with other agronomic information pertinent to the study are provided in Table 1.

Table 1 Agronomy background of field experiments during three consecutive growing seasons at Dickinson, ND, USA

Previous crop	2007–2008 Oat (grain)	2008–2009 Winter rye (grain)	2009–2010 Cover crop polyculture[a]
Cover crops			
Planting date	20 September	22 September	12 October
Seeding rate (live seed m^{-2})			
Cereal crops	745[b]	600	600
Hairy vetch	116	116	116
Date of termination attempt			
Disk	24 June	22 June	15 June
Sweep	24 June	22 June	24 June
Roller	24 June	30 June	28 June
Grain crops			
Planting date	3 July	30 June	2 July
Seeding rate (live seed m^{-2})			
Buckwheat	174	174	174
Pinto bean	16	16	16
Maize	5	5	5
Harvest date			
Buckwheat	15 September	15–16 September	20 September
Pinto bean	15 September	17–18 September	21 September
Maize	16 September	24 September	22 September

[a] A four-species cover crop mixture consisting of foxtail millet (*Setaria italica* [L.] P. Beauv.), forage turnip (*Brassica rapa* L.), oilseed radish (*Raphanus sativus* L.), and field pea (*Pisum sativum* L.) was seeded in April and disked in mid-July, 2009

[b] The cereal component in cereal–legume cover crop mixtures was reduced from 745 to 600 live seed per square meter

Winter rye and winter wheat were seeded at 600 live kernels m^{-2} (approx. 134 kg ha^{-1}) and hairy vetch at 116 live seed m^{-2} (approx. 130 kg ha^{-1}) when seeded alone or in mixtures, except in 2007 when cereal cover crops were seeded at 745 live kernels m^{-2} in sole crop plots. Established plants were counted in two, 0.25-m^2 areas within each plot approx 16 days after seeding and the following spring approximately 200 days after seeding to determine crop plant stand.

Cover crops were terminated using a light tandem disk, a Versatile 5,000 blade plow (Carr et al. 2012a) or wide-sweep undercutter, and a roller-crimper. The roller-crimper consisted of a hollow drum (41-cm diam.) with blunt blades welded in a chevron pattern (I & J Manufacturing LLC, Gap, PA). Cover crops were terminated by all three methods at 25 % anthesis (Zadoks growth stage 63; Zadoks et al. 1974) when treatments included winter rye (24 June) and winter wheat (2 July) in 2008, and at 50 % bloom (BBCH growth stage 65, using pea as model crop; Lancashire et al. 1991) in sole hairy vetch plots. Rolling-crimping was delayed until the early milk growth stage (Zadoks growth stage 73) of small-grains and flat pod growth stage (BBCH growth stage 70) in sole hairy vetch plots in subsequent years because of failure to kill cover crops at earlier growth stages in 2008. As a result, rolling-crimping was delayed 8 days compared with blade plowing and disking (22 June) in 2009, and 9 days compared with blade plowing (24 June) and 13 days compared with disking (15 June) in 2010. Cover crop and weed DM were determined just prior to termination by clipping above-ground biomass at the soil surface and separating into crop and weed subsamples from a 0.5-m^2 area in each plot and drying at 50 °C until a constant weight was maintained for at least 24 h.

Certified organic, common buckwheat (*Fagopyrum esculentum* Moench), 'Othello' pinto bean (*Phaseolus vulgaris* L.), and '08K12' maize were seeded into cover crops following termination using a low-disturbance, John Deere 750 planter on 3 July in 2008, 30 June in 2009, and 2 July in 2010. The grain crops were seeded in a direction perpendicular to the direction cover crops were seeded and terminated. Certified organic, pelleted "Nelson" Carrot (*Daucus carota* L.) and certified organic "FBC Dylan" spring wheat also were seeded in 2008 but had poor emergence (carrot) or high mortality after emerging (spring wheat) so were not seeded in 2009 or 2010. Conventional but untreated "Avalanche" navy bean (*P. vulgaris* L.) was seeded in 2008 but not in subsequent years because of an inability to obtain an organic seed source. Buckwheat was seeded at 174 live seed m^{-2} (approx 50 kg ha^{-1}) in rows spaced 15-cm apart while dry bean and maize each were seeded in rows 76-cm apart at rates of 16 live seed m^{-2} (approx. 67 kg ha^{-1}) for dry bean and 5 seed m^{-2} (approx. 16 kg ha^{-1}) for maize. Check strips where no grain crops were seeded were maintained across terminated cover crop treatments.

Buckwheat crop stand was determined roughly 3 weeks after seeding by counting plants in a 0.5-m^2 area selected randomly in each cover crop × termination method × grain crop sub-subplot. Dry bean and maize crop stand were determined at the same time but from a 2-m^2 area in each sub-subplot. End-of-season weed DM production was determined by clipping grass and broadleaf weed aboveground biomass from the soil surface within a 0.5-m^2 area randomly selected in each sub-subplot and drying at 50 °C until a constant weight was maintained. Weed DM production was determined just prior to harvesting grain crops during mid- to late-Sep, depending on the crop and year. Cover crop plants not killed by rolling-crimping or tillage were considered weeds and contributed up to 15 % of total weed DM production, based on visual estimates and depending on the year and cover crop treatment.

A self-propelled combine (Kincade Equip., Haven, KS, USA) was used to harvest grain directly from a 4.3-m^2 area in the center of each buckwheat sub-subplot in 2010. Short plant stature and other problems prevented buckwheat from being harvested mechanically in 2009, and pinto bean in both 2009 and 2010. In those years, grain yield was determined by clipping plants at the soil surface and threshing grain by hand from a 0.5- (buckwheat) to 2-m^2 (pinto bean) area in each sub-subplot. Maize was water stressed and failed to reach physiological maturity and produce harvestable grain in 2009 and 2010, and no crop produced harvestable grain in 2008. In those years, DM of maize and other crops was determined by harvesting and weighing plants from a 0.5- (buckwheat) to 2-m^2 (pinto bean and maize) area in each plot, collecting a 400- to 600-g subsample and recording fresh weight, then reweighing after drying to a constant weight.

Experimental design and statistical analyses

Plots were arranged in a split-split block in each field experiment with termination method comprising whole plots, cover crop treatments comprising subplots, and subsequent grain crops comprising sub-subplots. Sub-subplot dimensions were 3 by 3 m. All treatments and treatment combinations were replicated four times. Data were subject to ANOVA using the GLM procedure for balanced data available from SAS version 9.2 (SAS Institute, Inc., Cary, NC); treatments not common across all growing seasons (e.g., navy bean grown in 2008 but not in subsequent years) were not included in analyses. Termination methods, cover crops, and subsequent grain crops were considered fixed effects and blocks and years were considered random.

Combined analyses across years were not performed, in part, because cover crops were terminated during different growth stages and calendar dates across years, some changes in cover crop treatments were made after the first year of the study, and there were changes in the number of subsequent grain crops. The block×whole plot interaction was used to test whole plots (termination method) and the block×subplot (whole plot) interaction was used to test both subplots (cover crops) and the whole plot×subplot interaction. The block×sub-subplot interaction was used to test sub-subplots (grain crops) and the whole plot×sub-subplot interaction. Residual error was used to test the subplot×sub-subplot and whole plot×subplot×sub-subplot interactions. The F tests were considered significant at the $P<0.05$ level of significance. Mean comparisons using an F-protected LSD ($P=0.05$) were made to separate termination methods, cover crops, and subsequent grain crops.

Results

Growing conditions

Precipitation ranged from 93 mm in 2008 to 237 mm in 2010 from 15 June to 27 Sep (Fig. 1) at a weather station within 0.5 km of the field experiment (NDAWN 2012), coinciding closely with the earliest date that attempts to terminate cover crops were made to the latest date that grain crops were harvested across the field experiments. The 30-year average over this time period at Dickinson is 184 mm. August was abnormally dry in both 2009 and 2010 when less than 20 mm was received compared with the 30-year average of 42 mm. However, precipitation was near the 30-year average of 91 mm both years during June, and greater than the 30-year average of 56 mm in 2009 (78 mm) and particularly in 2010 (92 mm) during July. Late-season precipitation totaled 69 mm through 27 Sep in 2010 compared with the 30-year average of 41 mm, while 35 mm was received during that period in 2009. Dry conditions persisted throughout the 3.5-month period in 2008, with a majority of the precipitation received in events less than 10 mm during a rainfall event.

Temperatures were within 1 °C of the 30-year average for June through Sep during 2008, 2009, and 2010 (data not presented). Accumulated growing degree days for maize from mid-June to Sep totaled 1,830 in 2008, 1,648 in 2009, and 1,658 in 2010 (base minimum temperature=10 °C; NDAWN 2012). A minimum late-season temperature of 0 °C (light frost) was recorded on 28 Sep in 2009, and on both 17 and 18 Sep in 2010. Minimum temperatures failed to drop to 0 °C or below until 7 Oct in 2008. Late-season temperatures first dropped to −2 °C (heavy frost) or below on 9 Oct in 2008, 8 Oct in 2009, and 21 Oct in 2010.

Cover crop establishment and biomass production

Cereal crop density in spring (Table 2) was only 30 to 60 % of the targeted plant density (Table 1), depending on the year, crop species, and cover crop treatment. Still, density of cereal plants in spring was considered adequate for maximum DM production, based on previous research at Dickinson (data not provided). Density of plants was heavier for winter rye than winter wheat cover crop during fall (2 of 3 years) and spring (3 of 3 years), indicating greater success at establishing rye than wheat cover crop in this study (Table 2). Intercropping failed to affect plant stand relative to sole cropping in the 2008–2009 and 2009–2010 field experiments except in spring, 2009, when winter wheat density was lighter in intercrop than sole crop plots. Fewer rye plants occurred in intercrop than sole crop plots in the 2007–2008 field experiment, reflecting the lighter seeding rate for cereals in mixtures that growing season.

Plant density of hairy vetch cover crop in spring (Table 2) was only 11 to 32 % of the targeted plant stand (Table 1). In particular, density of hairy vetch cover crop was light during the 2009–2010 growing season and may be explained by the dry soil conditions that developed in August, 2009 (Fig. 1), which delayed establishment of fall-seeded hairy vetch until spring, 2010 (Table 2). Intercropping failed to affect plant density of hairy vetch compared with sole cropping except in

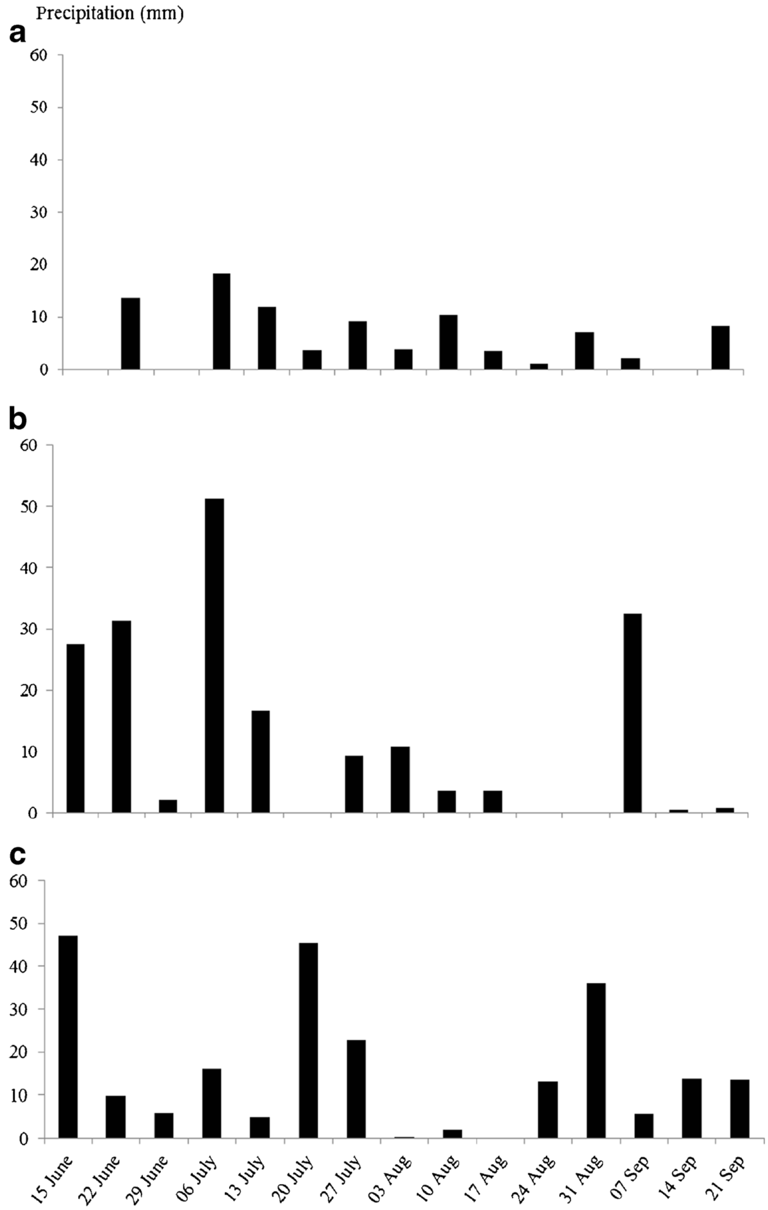

Fig. 1 Precipitation (millimeters) received weekly from 15 June to 27 Sep 27 (21 Sep) during 2008 (**a**), 2009 (**b**), and 2010 (**c**) at Dickinson, ND, USA

spring, 2007, when hairy vetch density was depressed in intercropped plots.

An interaction between termination method and cover crop treatment was not detected for DM production by cover crops during any growing season (data not provided). Greater amounts of DM were produced by cereal and hairy vetch cover crops when rolled-crimped than disked during 2008–2009 and 2009–2010 growing seasons (Table 3). This difference in DM production was expected since cover crops were rolled-crimped up to 13 days later than disked to improve killing effectiveness of the roller-crimper, thereby allowing the accumulation of additional DM by cover crops. Winter rye produced equal or greater amounts of DM compared with winter wheat across termination methods. Intercropping generally failed to affect DM production by cereal cover crops, while intercropping reduced DM production by hairy vetch from 67 to 96 %, depending on the cover crop treatment and growing season. Differences in hairy vetch DM production when intercropped with rye and wheat were not detected, suggesting the lack of a competitive differential between the two cereal crops. This contrasts with previous research indicating that winter rye is more competitive

Table 2 Plant density of winter rye or winter wheat (Cereal) cover crops and hairy vetch (Legume) cover crop during three growing seasons at Dickinson, ND, USA

Cover crop	2007–2008				2008–2009				2009–2010			
	Cereal		Legume		Cereal		Legume		Cereal		Legume	
	Fall	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall	Spring
Plants m^{-2}												
Hairy vetch (HV)	–	–	62	37 a	–	–	36	32	–	–	–	13
Winter rye (WR)	503 a	472 a	–	–	284	243 a	–	–	194 a	372 a	–	–
Winter wheat (WW)	381 b	222 c	–	–	253	215 b	–	–	89 b	257 bc	–	–
HV+WR	392 b	364 b	45	11 b	281	243 a	25	27	207 a	310 ab	–	13
HV+WW	342 b	194 c	40	15 b	208	187 c	21	31	67 b	219 c	–	12
LSD	72	63	NS	11	NS	25	NS	NS	88	80		NS
P value	<0.01	<0.001	0.41	<0.01	0.21	<0.01	0.12	0.75	0.01	<0.01		0.94

Different letters after numbers in columns indicate that differences in treatment means were detected at $P<0.05$

than other winter cereals when grown with dicots (Beres et al. 2010).

An interaction between termination method and cover crop treatment was not detected for weed DM production prior to cover crop termination during any growing season (data not provided). Likewise, differences were not detected in weed DM across termination methods, even though rolling-crimping was done later than disking or

Table 3 Impact of cover crop termination method (disking (Disk), wide-sweep undercutting with a blade plow (Sweep), and rolling-crimping (Roller)) and species or species mixture on dry matter production of hairy vetch (HV), winter rye (WR), winter wheat (WW), and cereal-vetch cover crops over 4 years at Dickinson, North Dakota, USA

	2007–2008[a]		2008–2009		2009–2010	
	Cereal	Legume	Cereal	Legume	Cereal	Legume
Termination method						
Disk	–	–	3,384 b[b]	220 b	2,867 b	294 b
Sweep	–	–	3,420 b	187 b	4,345 a	533 b
Roller	–	–	4,892 a	570 a	3,979 a	1,349 a
$LSD_{0.05}$			1,190	221	811	586
P value			0.03	0.02	0.01	0.01
Cover crop						
Hairy vetch (HV)	–	1,728 a	–	702 a	–	1,633 a
Winter rye (WR)	3,615 a	–	4,919 a	–	4,053	–
Winter wheat (WW)	4,113 a	–	3,182 b	–	3,821	–
HV+WR	3,460 a	75 b	4,673 a	44 b	3,848	191 b
HV+WW	2,397 b	368 b	2,821 b	231 b	3,201	352 b
$LSD_{0.05}$	748	870	721	222	NS	462
P value	<0.01	<0.01	<0.001	<0.001	0.32	<0.001

[a] Termination methods were applied at the same vegetative growth stage in 2007–2008 so aboveground dry matter production was determined for subplot treatments (cover crop species) but not whole plot treatments (termination method); disking was done prior to rolling in both 2008–2009 and 2009–2010 growing seasons so impact of whole plot and subplot treatments were determined

[b] Different letters after numbers indicate that differences in treatment means were detected at $P<0.05$

undercutting in 2008–2009 and 2009–2010 growing seasons (Table 4). Weed DM differences were not detected across cover crop treatments that included a cereal component, while DM production was more than 10 times greater in hairy vetch sole crops compared with winter rye sole crop plots during all three growing seasons, and in two of the three growing seasons compared with winter wheat sole crop plots, indicating the superior ability of fall-seeded cereals to compete with weeds. Others reported that hairy vetch is not as competitive with weeds as are cereal crops (Nelson et al. 1991). Broadleaf weed composition was dominated by Russian thistle (*Salsola kali* L. var. *tenuifolia* Tausch) and common lambsquarters (*Chenopodium album* L.), with smaller proportions of other annual weeds (e.g., redroot pigweed; *Amaranthus retroflexus* L.) and hairy vetch not killed earlier by roller-crimping or other methods. Perennial broadleaf weed species were not present. Grass weed composition was dominated almost exclusively by equal proportions of green foxtail (*Setaria viridis* [L.] Beauv.) and barnyardgrass (*Echinochloa crusgalli* [L.] Beauv.).

Table 4 Weed dry matter production across cover crops at termination by disking (Disk), undercutting with a wide-sweep blade plow (Sweep), and rolling-crimping (Roller) over 4 years at Dickinson, ND, USA

	2007–2008 (kg ha^{-2})	2008–2009 (kg ha^{-2})	2009–2010 (kg ha^{-2})
Termination method			
Disk	–[a]	528	20
Sweep	–	819	81
Roller	–	614	152
$LSD_{0.05}$		NS	NS
P value		0.29	0.3
Cover crop			
Hairy vetch (HV)	362a[b]	2202a	357a
Winter rye (WR)	<1b	16b	8b
Winter wheat (WW)	9b	458b	22b
HV+WR	4b	17b	7b
HV+WW	22b	574b	27b
$LSD_{0.05}$	251	738	206
P value	<0.05	<0.001	<0.05

[a] Termination methods were applied at the same vegetative growth stage in 2007–2008 so aboveground dry matter production was determined for cover crop treatments in undercut whole plots only but not in other whole plots; disking was done prior to rolling in both 2008–2009 and 2009–2010 growing seasons so impact of whole plot and subplot treatments were determined

[b] Different letters after numbers in columns indicate that differences in treatment means were detected at $P<0.05$

Establishment and yield of grain crops following cover crops

An interaction was detected between cover crop termination method and subsequent grain crops for grain crop plant density during both the 2007–2008 growing season ($P=0.005$) and 2009–2010 ($P<0.001$) growing seasons. Fewer buckwheat plants occurred as tillage was reduced when terminating cover crops during the 2007–2008 growing season, while both dry bean and maize plant densities were low but unaffected by cover crop termination method (Fig. 2). Similarly, buckwheat plant numbers were greater when the cover crop was terminated by disking than by undercutting or rolling-crimping during the 2009–2010 growing season, while termination method did not affect plant density of dry bean and maize. An interaction between cover crop termination method and subsequent grain crops for plant stand was not detected during the 2008–2009 growing season ($P=0.40$); plant density was heavier for buckwheat than both dry bean and maize (data not presented).

Maize failed to produce grain during any growing season, probably because of only partial soil water recharge after planting grain crops, and the limited number of heat units that remained in any growing season after maize plants emerged. Grain yield across subsequent buckwheat and dry bean crops averaged only 487 kg ha^{-1} in plots where previous cover crops were disked during the 2008–2009 growing season, but was higher following wheat-vetch (705 kg ha^{-1}) and hairy vetch (680 kg ha^{-1}) than the other three cover crop treatments (Fig. 3). Grain yield was low consistently when a roller-crimper was used regardless of previous cover crop, averaging only 37 kg ha^{-1} across the five treatments. Differences were not detected ($P=0.50$) between buckwheat and dry bean for grain yield, and an interaction between termination method and grain crop did not occur.

Grain yield was estimated visually to be low (<40 kg ha^{-1}) for buckwheat and dry bean in undercut and rolled-crimped plots during the 2009–2010 growing season so grain was not harvested. More grain was produced by buckwheat (80 kg ha^{-1}) than dry bean (48 kg ha^{-1}) across the five cover crops in disked plots, although these low yields have little relevance to

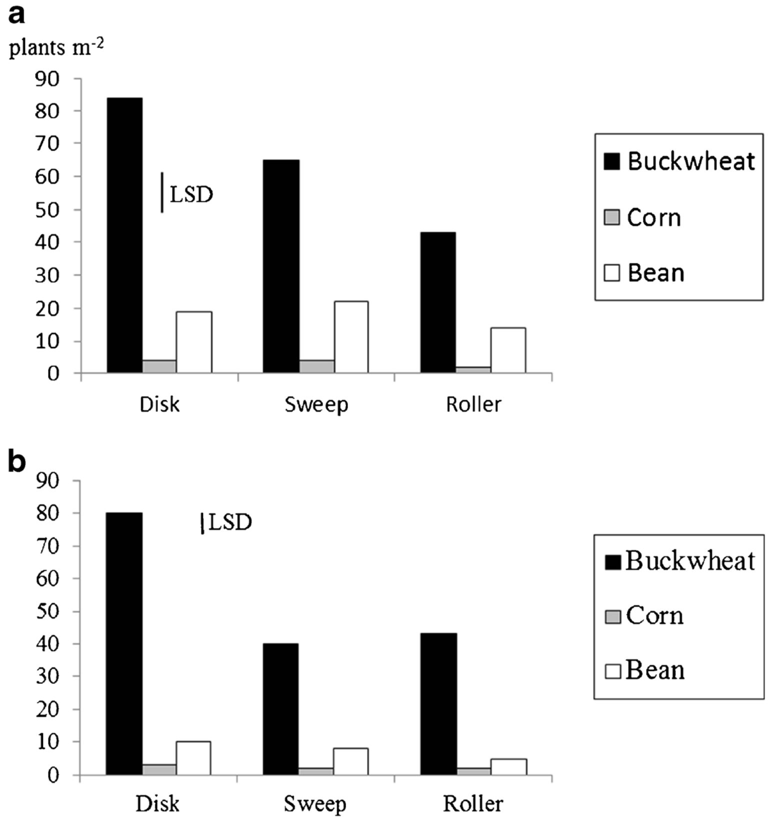

Fig. 2 Plant counts of three grain crops seeded after disking (*Disk*), undercutting with a wide-sweep blade plow (*Sweep*), and rolling-crimping (*Roller*) across five cover crop treatments during 2007–2008 (**a**) and 2009–2010 (**b**) growing seasons in southwestern North Dakota, USA. Heights of any bars within a figure that differ more than the LSD are significantly different at the $P<0.05$ level

commercial organic operations. As with maize, grain was not produced by buckwheat and dry bean in the 2007–2008 field experiment.

Aboveground DM production by grain crops was limited and reflected the low grain yields that were produced in this study. For example, while aboveground DM production was greater following rolled-crimped hairy vetch than any other combination of cover crop treatment and termination method during the 2007–2008 growing season, only 510 kg ha^{-1} of aboveground DM was produced following rolled-crimped hairy vetch (Fig. 4a). Similarly, maize produced greatest amounts of aboveground DM following disked hairy vetch and disked wheat-vetch cover crops during the 2008–2009 growing season, but DM yield across these two treatments averaged less than 1,800 kg ha^{-1}

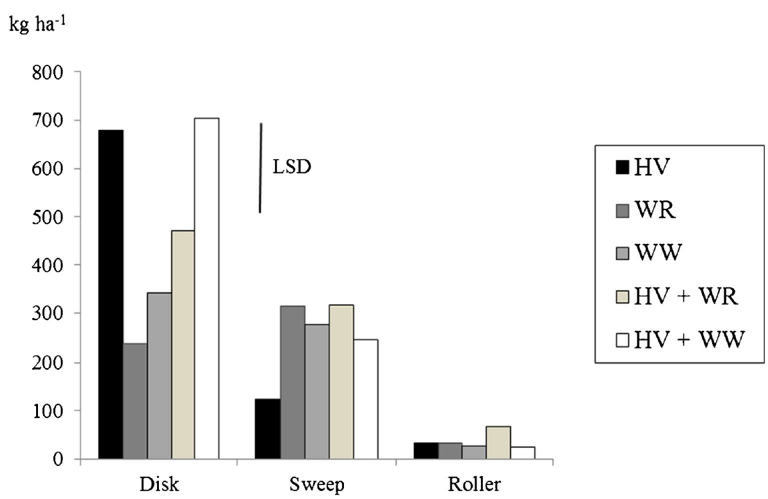

Fig. 3 Combined grain yield of buckwheat and dry bean seeded into hairy vetch (*HV*), winter rye (*WR*), and winter wheat (*WW*) cover crops along with cereal-vetch cover crop mixtures terminating by disking (*Disk*), undercutting with a wide-sweep blade plow (*Sweep*), and rolling-crimping (*Roller*) during the 2008–2009 growing season in southwestern North Dakota, USA. Heights of any bars within a figure that differ more than the LSD are significantly different at the $P<0.05$ level

(Fig. 4b). Aboveground DM production totaled 2,921 kg ha^{-1} in disked plots across the five cover crop treatments during the 2009–2010 growing season, compared with 259 kg ha^{-1} in rolled plots (data not provided). An interaction between cover crop treatment and termination method was not detected for DM production of the subsequent grain crop during the 2009–2010 growing season (data not provided), while interactions were detected during the previous two growing seasons (Fig. 4).

Aboveground dry matter yield of weeds at harvest

Interactions were detected in aboveground weed DM at grain crop harvest between previous cover crop and termination method in two of three growing seasons. Aboveground weed DM was greatest (1,204 kg ha^{-1}) at grain crop harvest following rolled-crimped hairy vetch cover crop during the 2007–2008 growing season (Fig. 5b). Disking hairy vetch also cut and buried weeds, resulting in less weed DM than terminating hairy vetch by rolling-crimping, although weed DM production still was greater following hairy vetch than other cover crops that were terminated by disking, except for rye-vetch intercrop. Weed DM production was relatively low in plots where cereal crops were grown alone or, in all but one instance, intercropped with hairy vetch.

More weed DM occurred at grain crop harvest following hairy vetch than other cover crops that were rolled-crimped or undercut during the 2009–2010 growing season (Fig. 5a). Conversely, no differences were detected in aboveground weed DM in plots following a previous hairy vetch cover crop and other cover crops

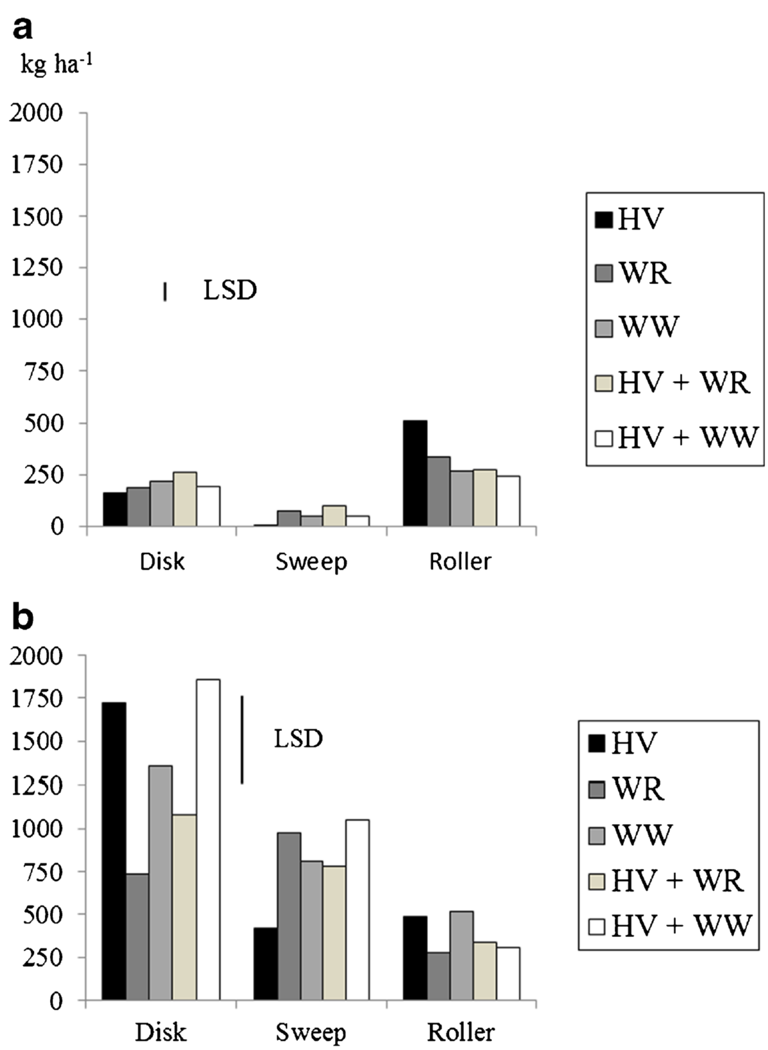

Fig. 4 Dry matter production across buckwheat, dry bean, and maize grain crops seeded into hairy vetch (*HV*), winter rye (*WR*), and winter wheat (*WW*) cover crops along with cereal-vetch cover crop mixtures terminating by disking (*Disk*), undercutting with a wide-sweep blade plow (*Sweep*), and rolling-crimping (*Roller*) during 2007–2008 (**a**) and 2008–2009 (**b**) growing seasons in southwestern North Dakota, USA. Heights of any bars within a figure that differ more than the LSD are significantly different at the *P*<0.05 level

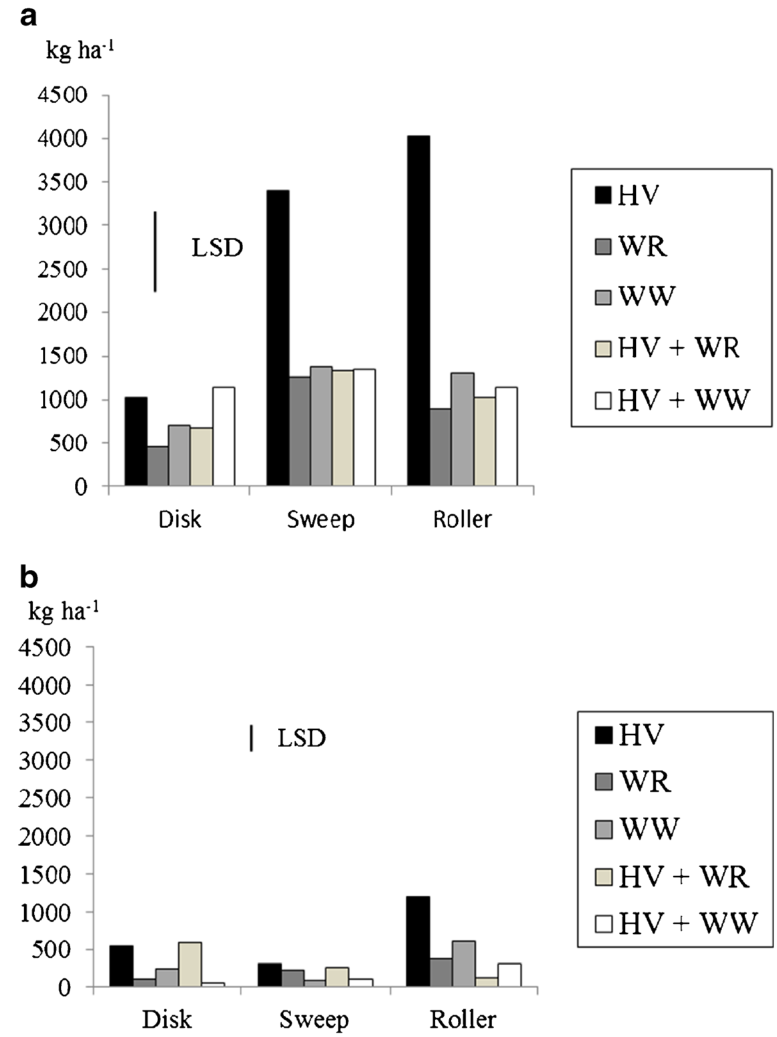

Fig. 5 Weed dry matter at harvest of grain crops seeded into hairy vetch (*HV*), winter rye (*WR*), and winter wheat (*WW*) cover crops along with legume-cereal cover crop mixtures terminating by disking (*Disk*), undercutting with a wide-sweep blade plow (*Sweep*), and rolling-crimping (*Roller*) during 2009–2010 (**a**) and 2007–2008 (**b**) growing seasons in southwestern North Dakota, USA. Heights of any bars within a figure that differ more than the LSD are significantly different at the $P<0.05$ level

treatments in plots that were disked. Other differences in weed DM production between cover crop treatments generally were not detected An interaction in above-ground weed DM at grain crop harvest between previous cover crop and termination method was not detected during the 2008–2009 growing season (data not provided).

Weed DM production at grain crop harvest was unaffected by the grain crop that was grown. Likewise, growing grain crops after terminating cover crops failed to affect subsequent weed DM production compared with not growing a grain crop, except during the 2007–2008 growing season. In that growing season, weed DM production was greater in plots without grain crops (609 kg ha^{-1}) than in buckwheat (290 kg ha^{-1}), dry bean (263 kg ha^{-1}), or maize (270 kg ha^{-1}) plots. There was a non-significant trend ($P=0.08$) for weed DM production to be less at grain harvest in buckwheat (317 kg ha^{-1}) plots than dry bean (652 kg ha^{-1}), maize (805 kg ha^{-1}), and no-grain-crop plots (808 kg ha^{-1}) during the 2008–2009 growing season.

Discussion

Yields were low and, in some instances, nonexistent when grain crops followed cover crops in this study. Some enhancement in yield occurred when cover crops were disked or undercut at an earlier date than rolled-crimped, probably in part because of soil water benefits that resulted from earlier termination of cover crops. It was necessary to delay rolling-crimping until advanced growth stages of cover crops so that killing effectiveness was maximized. Even then, cover crop termination by rolling-crimping was never successful completely, with killing proficiency as low as 85 %, based on visual estimates. Surviving cover crop plants competed with subsequent grain crops for the limited amounts of water that were available during the July through early-Sep period. The ability of growing grain crops successfully after rolling-crimping cover crops depends heavily on precipitation received following cover crop termination since soil water reserves may be depleted by cover crops.

It is unlikely that enough precipitation is received to support a single-season cover crop/grain crop relay system in semiarid regions, particularly when cover crops are not terminated until reaching reproductive growth stages. For example, precipitation averaged only 139 mm from 01 July to 30 Sep across the three growing seasons included in this study, coinciding roughly to the time that grain crops could be grown following rolled-crimped cover crops. Not all of this limited precipitation was available subsequently to crop plants because of evaporation and other factors, likely resulting in water-stress conditions and making production of high grain yields impossible.

Tillage treatments could have been imposed at earlier calendar dates than in this study, allowing grain crops to be seeded earlier than was done in tilled plots. However, the impact on subsequent grain crops and weeds likely would be negligible if cover crops were terminated too early in spring at upper latitudes where early season growth is limited by cold temperatures. Soil water recharge could be limited if grain crops were seeded too soon after cover crops were terminated in tilled plots. Seeding grain crops at different times also would have confounded comparisons between cover crops and termination methods for grain crop performance since seeding dates of grain crops would have varied along with the timing of cover crop termination.

Delaying the rolling-crimping of cover crops until reproductive growth stages were reached resulted in seeding grain crops 4 to 8 weeks later than the last recommended date in this study, depending on the crop and year. A short-season maize hybrid was seeded within 60 min of rolling-crimping cover crops, but only a limited number of growing degree days remained (1648 to 1830, depending on the year; NDAWN 2012), making it difficult to produce grain before the first killing freeze in the fall. This delay in seeding date coupled with limited amounts of precipitation and stored soil water explains the poor performance of grain crops in the cover crop/grain crop relay system that was considered. We speculate that spring- or summer-seeded grain crops can be grown successfully when seeded into rolled-crimped cover crops in semiarid regions when a cover crop/grain crop system is spread over multiple growing seasons. This approach has been considered in the Canadian prairie region, where organic spring wheat was grown following pea-oat and pea sole crop cover crops that were rolled-crimped the previous growing season (Vaisman et al. 2011). Wheat yield was depressed in rolled-crimped compared with tilled plots in two of three site-years because of soil fertility deficiencies in that study, emphasizing the need for strategies that supply adequate nutrition to grain crops following rolled-crimped cover crops in organic systems.

An alternative approach to growing grain crops the season after cover crops are rolled-crimped is to sow fall-seeded grain crops into cover crops that were rolled-crimped earlier in summer. This approach is best suited to dry regions where limited if any decomposition of rolled-crimped mulch would occur between the time that cover crops were killed and fall-seeded grain crops were seeded. At the same time, sufficient late-season precipitation would be needed so that fall-seeded grain crops could become established before temperatures dropped below freezing. This approach has been investigated in Montana (Carr et al. 2012a) and deserves further investigation.

Aboveground weed DM was comparable in rolled-crimped plots compared with disked plots at grain crop harvest in our study, except when hairy vetch was grown. Amounts of weed DM suggest good weed control was provided by cover crop mulch in some instances (e.g., total weed DM of 120 kg ha^{-1} at grain crop harvest following rolled-crimped rye and vetch cover crop mixture during the 2007–2008 growing season), but not in others (e.g., total weed DM of 1, 305 kg ha^{-1} following rolled-crimped winter wheat cover crop during the 2009–2010 growing season). Large amounts of weed DM at grain crop harvest generally reflects a weed population making a significant contribution to the weed seed bank when annual species like those that dominated the weed population in this study are present. The apparent lack of control provided by rolled-crimped cover crop mulch in some instances may also reflect the poor growth and lack of competition provided by the grain crops grown following cover crops, rather than the weed suppressive ability of cover crop mulch. Still, these results support suggestions by

Mirsky et al. (2012) that consistent weed control is the greatest obstacle to growing grain crops successfully following rolled-crimped cover crops.

Challenges must be overcome before successful production of grain crops after rolling-crimping cover crops can be accomplished consistently in semiarid regions. However, the potential benefits derived from replacing tillage with zero-till methods in dry regions supports a sustained effort to develop organic systems that rely on vegetative mulch produced by killed cover crops for weed suppression. Persistence and collaboration among scientists was essential in the development of zero-till methods used successfully by conventional farmers today. A similar approach, with the participation of farmers in the research and development process, is recommended to solve current problems and create zero-till methods suitable for adoption by commercial organic farmers in semiarid regions.

References

Ashford DL, Reeves WD (2003) Use of a mechanical roller-crimper as an alternative kill method for cover crops. Am J Altern Agric 18:37–45. doi:10.1079/AJAA200232

Beres BL, Harker KN, Clayton GW, Bremer E, Blackshaw RE, Graf RJ (2010) Weed-competitive ability of spring and winter cereals in the northern Great Plains. Weed Technol 24: 108–116. doi:10.1614/WT-D-09-00036.1

Carr PM, Anderson RL, Lawley YE, Miller PR, Zwinger SF (2012a) Organic zero-till in the northern US Great Plains region: opportunities and obstacles. Renew Agric Food Syst 27:12–20. doi:10.1017/S174217051100041X

Carr PM, Mäder P, Creamer NG, Beeby JS (2012b) Editorial: overview and comparison of conservation tillage practices and organic farming in Europe and North America. Renew Agric Food Syst 27:2–6. doi:10.1017/S1742170511000536

Creamer NG, Dabney SM (2002) Killing cover crops mechanically: review of recent literature and assessment of new research results. Am J Altern Agric 17:32–40. doi:10.1079/AJAA200014

Creamer NG, Plassman B, Benett MA, Wood RK, Stinner BR, Cardina J (1995) A method for mechanically killing cover crops to optimize weed suppression. Am J Altern Agric 10: 157–162

Delate K, Cwach D, Chase C (2012) Organic no-tillage system effects on soybean, corn and irrigated tomato production and economic performance in Iowa, USA. Renew Agric Food Syst 27:49–59. doi:10.1017/S174270511000524

Grandy AS, Robertson GP, Thelen KD (2006) Do productivity and environmental trade-off justify periodically cultivating no-till cropping systems. Agron J 98:1377–1383. doi:10.2134/agronj2006.0137

Kettler TA, Lyon DJ, Doran JW, Powers WL, Stroup WW (2000) Soil quality assessment after weed-control tillage in a no-till wheat-fallow cropping system. Soil Sci Soc Am J 64:339–346

Kornecki TS, Price AJ, Raper RL, Arriaga FJ (2009) New roller crimper concepts for mechanical termination of cover crops in conservation agriculture. Renew Agric Food Syst 24:165–173. doi:10.1017/S1742170509002580

Lancashire PD, Bleiholder H, Van Den Boom T, Langeluddeke PP, Stauss R, Weber E, Witzenberger A (1991) A uniform decimal code for growth stages of crops and weeds. Ann Appl Biol 119:561–601

Luna JM, Mitchell JP, Shrestha A (2012) Conservation tillage for organic agriculture: evolution toward hybrid systems in the western USA. Renew Agric Food Syst 27:21–30. doi:10.1017/S1742170511000494

Mäder P, Berner A (2012) Development of reduced tillage systems in organic farming in Europe. Renew Agric Food Syst 27:7–11. doi:10.1017/S1742170511000470

Mirsky SB, Matthew RR, Curran WS, Teasdale JR, Maul J, Spargo JT, Moyer J, Grantham AM, Weber D, Way TR, Camargo GG (2012) Conservation tillage issues: cover crop-based organic rotational no-till grain production in the mid-Atlantic region, USA. Renew Agric Food Syst 27:31–40. doi:10.1017/S174270511000457

Moyer J (2011) Organic no-till farming. Acres USA, Austin TX

NDAWN (2012) North Dakota agricultural weather network. http://www.ndawn.ndsu.nodak.edu/. Accessed 12 February 2013

Nelson WA, Kahn BA, Roberts BW (1991) Screening cover crops for use in conservation tillage systems for vegetables following spring plowing. HortSci 26:280–282

Peigné J, Ball BC, Roger-Estrade J, David C (2007) Is conservation tillage suitable for organic farming? Soil Use Manag 23: 129–144. doi:10.1111/j-1475-2743.2006.00082.x

Reberg-Horton SC, Grossman JM, Kornecki TS, Meijer AD, Price AJ, Place GT, Webster TM (2012) Utilizing cover crop mulches to reduce tillage in organic systems in the southeastern USA. Renew Agric Food Syst 27:41–48. doi:10.1017/S1742170511000469

Shirtliffe SJ, Johnson EN (2012) Progress towards no-till organic weed control in western Canada. Renew Agric Food Syst 27: 60–67. doi:10.1017/S1742170511000500

Teasdale JR (1996) Contribution of cover crops to weed management in sustainable agriculture systems. J Prod Agric 9:475–479

Vaisman I, Entz MH, Flaten DN, Gulden RH (2011) Blade roller-green manure interactions on nitrogen dynamics, weeds, and organic wheat. Agron J 103:879–889. doi:10.2134/agronj2010.0437

Wortmann CS, Quincke A, Drijber RA, Mamo M, Franti T (2008) Soil microbial community change and recovery after one-time tillage of continuous no-till. Agron J 100:1681–1686. doi:10.2134/agronj2007.0317

Zadoks JC, Chang TT, Konzak CF (1974) A decimal code for the growth stage of cereals. Weed Res 14:415–421