agronomy

MDPI

Article

Weed Control with Cover Crops in Irrigated Potatoes

G.H. Mehring *,†, J.E. Stenger and H.M. Hatterman-Valenti †

Received: 31 October 2015; Accepted: 24 December 2015; Published: 5 January 2016
Academic Editor: Herb Cutforth

Department of Plant Sciences , North Dakota State University, P.O. Box 6050, Fargo, ND 58108-6050, USA; john.stenger@ndsu.edu (J.E.S.); h.hatterman.valenti@ndsu.edu (H.M.H.-V.)
* Correspondence: grant.mehring@ndsu.edu; Tel.: +1-701-429-7434
† These authors contributed equally to this work.

Abstract: Field experiments at Oakes, ND, USA in 2010 and Carrington, ND, USA in 2011 were conducted to evaluate the potential for cover crops grown in the Northern Great Plains, USA in order to reduce weed emergence and density in irrigated potatoes. Treatments included five cover crop treatments and three cover crop termination treatments. Termination of cover crops was done with glyphosate, disk-till, and roto-till. Cover crop biomass accumulation was greatest for rye/canola and triticale at Oakes, and hairy vetch and hairy vetch/rye at Carrington. Cover crop and termination affected weed control 14, 29, and 51 days after planting (DAP) at Oakes. Weed control at Carrington was at least 90% for all cover crop and termination treatments at all three evaluation timings. Marketable yield at Oakes was greater when roto-till was used to terminate the cover crops compared with disk-till or herbicide, which is beneficial for organic systems where herbicides are not used. Marketable yield at Carrington was not affected by cover crop or termination treatments. Results suggest that cover crops can successfully be integrated into irrigated potato production for weed control with yields equal to no cover crop, and with attention to potential mechanical difficulties.

Keywords: cover crops; weed suppression; potato production

1. Introduction

Potato (*Solanum tuberosum* L.) production in conventional agriculture is an intensive process from seed bed preparation to pest control, while ensuring high yields through fertility and hill management [1]. Cover crops are increasingly used in agriculture but are not currently used to produce potatoes, even though their benefits have been researched during production [2,3]. Winter annual cover crops are primarily grown in the Northern Great Plains during the late summer and fall months, planted from the middle of August onwards. This timing does not preclude growing a cash crop but often limits the production of crops with longer growing seasons [4,5].

Rye (*Secale cereale* L.) and triticale (*Triticum durum* L.) are winter hardy when used as cover crops planted in the fall, with extensive root systems and quick accumulation of biomass [6]. Hairy vetch (*Vicia villosa* Roth) is a nitrogen-fixing legume that vines extensively and provides excellent soil cover [6]. A combination of hairy vetch and rye is useful as the hairy vetch climbs and vines on the rye and the two in combination provide nitrogen-fixing, prevent nitrogen leaching, and provide better cover and residue accumulation than either species in monoculture. Turnip (*Brassica rapa* L.), radish (*Raphanus sativus* L.), and canola (*Brassica napus* L.) are capable of being used as cover crops. Turnip and radish can decrease soil compaction and increase nutrient capture [7,8].

Illustrating the importance of weed control in potato production, Nelson and Thoreson [9] found that yields were reduced an average of 54% for cultivars "Norchip" and "Viking" if no weeds were controlled during the season. In another study, it was reported that "Red Norland" and "Red Pontiac" tuber yields were reduced 65% and 45%, respectively, in zero weed control plots [10]. When weeds were controlled for the first three weeks after the potatoes emerged, the yield lost was only 16%.

The most cost effective and widely used weed control method for potato production is cultivation [11]. In addition, cultivation reduces tuber greening from the exposure of potatoes to sunlight [12]. A constraint to cultivation is the potential for decreased yield with additional cultivation, due to either lateral root pruning or soil compaction resulting in increased soil density [9]. Therefore, producers strive to have only one cultivation per season that is done after planting. Another constraint to cultivation is weather conditions that prevent timely cultivation and result in increased weed infestations [11].

Herbicides are available for use in potatoes, with the most common being metribuzin [13]. However, prominent weeds in potato growing regions of the United States, specifically the nightshade family, are not consistently controlled with herbicide [14]. An additional concern with the use of herbicides in potato is weed resistance, with many known herbicide resistant weeds such as redroot pigweed (*Amaranthus retroflexus* L.) and common lambsquarters (*Chenopodium album* L.) [15].

Cover crops are capable of suppressing weeds if they produce high biomass, are easily terminated, suppress weed seed germination, grow long enough to minimize weed-crop competition, and do not interfere directly with crop growth [16]. Cover crops control weeds by competition, allelopathy, weed seed decay in the seed bank, and the proliferation of residue [17]. Weed control when using a cover crop is dependent upon the amount of biomass on the soil surface and incorporated into the soil [18]. Cover crop residues have not been shown to control weeds the entire growing season, nor have they been shown to control every weed in the field [4]. Cover crops such as hairy vetch and rye require extra time in the spring to reach their maximum growth and biomass accumulation, thus delaying potato planting by several weeks from the earliest possible planting date [19]. No-till potato systems have been researched, with yields comparable to conventional-till with proper use of modified planters and preparation of the cover crop before planting [16,19]. The style of mower may influence weed control with cover crops, with flail mowing being the most effective [20].

The first objective of this study was to determine if cover crops provided effective weed control in potato production. The second objective was to determine how cover crops influenced potato yields.

2. Results and Discussion

2.1. Cover Crop Biomass

Cover crop biomass accumulation was greater for rye/canola and triticale compared with the turnip/radish cover crop at Oakes in 2010 (Table 1). Biomass in the no cover crop treatment was from the combined weed growth present, as this was not a weed-free check. The rye and triticale treatments accumulated far less than reported in the Eastern U.S. due to less soil moisture and a longer favorable growing season but above the level reported to suppress weeds in greenhouse studies [18]. Cover crops were terminated prior to anthesis of the cereal crops rye and triticale. De Bruin *et al.* [21] found significant rye regrowth when mowed at growth stages before anthesis. Rye and triticale terminated 1 June did not exhibit regrowth in treatments where mowing was followed by a termination treatment of roto-till or disk-till.

Hairy vetch and hairy vetch/rye accumulated greater biomass than no planted cover crop at Carrington in 2011 (Table 1). Hairy vetch in monoculture accumulated biomass equal to what has been reported in the Eastern U.S [18]. Biomass for the no cover crop treatment was from a combination of weed species and was low at 54 kg· ha^{-1}, harvested on 15 June. In comparison, Oakes during 2010, had an average of 2186 kg· ha^{-1} of weed biomass harvested on 1 June, illustrating the difference in weed pressure between the two locations. Rye and triticale biomass accumulations were lower than expected when allowed to mature until 15 June. Environmental conditions in the spring included cool temperatures and wet soil, which may have contributed to the low biomass accumulations of the cereals at Carrington. Cover crops terminated 15 June did not exhibit regrowth in treatments where mowing was followed by a termination treatment of roto-till or disk-till.

Table 1. Average dry weight biomass for cover crop treatments at Oakes, ND, USA, 2010 and Carrington, ND, USA, 2011.

Cover Crop	Oakes	Carrington
	kg· ha^{-1}	
Rye/canola	5892	-
Triticale	5551	1850
Rye	4954	1671
No cover crop	2186	54
Turnip/radish	2115	-
Hairy vetch	- [x]	3996
Rye/hairy vetch	-	3580
LSD [z]	2995	2495

[z] Means followed by the same letter within a column and location are not significantly different according to Fisher's Protected LSD ($p \leqslant 0.05$); [x] Treatment was not included at this environment.

Hairy vetch is only moderately hardy in northern climates [22]. In certain locations throughout the Midwest, there are offerings of variety-not-stated hairy vetch. Hairy vetch did not winter-kill during 2010–2011, though it did winter-kill during 2009–2010, with both locations within USDA hardiness zone 4a. Hairy vetch seed planted in 2009 was labeled as a product from Oregon, while the hairy vetch seeded almost one full month earlier in 2010 was a genotype selected by the Carrington Research and Extension Center in North Dakota, specifically for winter hardiness. This seed source resulted in a dense and winter hardy stand of hairy vetch in 2011 (Table 1).

2.2. Weed Control

Weed species present at Oakes included common lambsquarters, redroot pigweed, hairy nightshade (*Solanum sarrachoides* Sendtner), yellow foxtail (*Setaria glauca* L. *Beauv.*), Pennsylvania smartweed (*Polygonum pensylvanicum*), and common purslane (*portulaca oleracea* L.). Weed species present at Carrington included common lambsquarters, redroot pigweed, yellow foxtail, wild buckwheat (*Polygonum convolvulus* L.), and Eastern black nightshade (*Solanum ptycanthum Dun.*). No selective control of any specific weed species were observed from any treatment (data not shown). Since so few grass species were present and broadleaf weed species responded similarly, the weed analysis was combined over species and analyzed as total weeds and average weed control.

Cover crop and termination method affected average weed control 14 and 29 days after planting (DAP) at Oakes. At 14 DAP, rye and rye/canola had at least 93% weed control regardless of the termination method (Table 2). In contrast, turnip/radish had less than 90% weed control regardless of the termination method. Triticale, turnip/radish, and no cover crop had greater weed control when terminated by herbicide than disk-till termination. The results were expected for the two cover crops with the least amount of biomass since disk-tilling would not distribute the biomass as uniformly as the herbicide termination but was not expected for triticale. At 29 DAP, triticale, rye, and rye/canola terminated by roto-tilling and rye terminated by disk-till had greater average weed control compared with other cover crop and termination treatments. Beneficial effects when weeds are controlled early in the season have been demonstrated previously, with a 30% to 50% potato yield increase when weeds were controlled for three weeks after potato emergence compared with no weed control the entire season [9].

Table 2. Effect of cover crop and termination method on average weed control 14 and 29 days after planting averaged, Oakes, ND, USA, 2010.

	Cover Crop					
Termination Method	**Triticale**	**Rye**	**Turnip/Radish**	**Rye/Canola**	**No Cover Crop**	**Mean**
	% Control					
14 DAP						
Disk-till	88	93	79	93	81	87
Roto-till	93	95	89	94	- [x]	93
Herbicide	95	95	89	95	91	93
Mean	92	94	86	94	86	
LSD_1 [z]	4					
LSD_2 [y]	3					
29 DAP						
Disk-till	86	95	84	88	70	85
Roto-till	94	93	88	93	- [x]	92
Herbicide	89	85	89	90	83	87
Mean	90	91	87	90	77	
LSD_1	4					
LSD_2	3					

[z] LSD_1 was calculated to compare all levels of cover crop for the same termination method according to Fisher's Protected LSD ($p \leqslant 0.05$); [y] LSD_2 was calculated to compare all levels of termination method for the same cover crop method according to Fisher's Protected LSD ($p \leqslant 0.05$).

The first cultivation occurred after the first weed control evaluation, redistributing the biomass from the various cover crops. Results suggest that the redistribution of triticale, rye, and rye/canola biomass from cultivation did not reduce weed control at 29 DAP when roto-tilling was the termination method. The exception was the 95% weed control with rye cover crop and disk-till termination, which may have been attributed to the allelopathic capabilities of the rye. Moore *et al.* [23] reported significantly lower redroot pigweed control for a triticale cover crop when it was terminated with glyphosate in no-till soybean compared with a glyphosate-terminated rye cover crop. The differences were attributed to the allelopathic capabilities of the rye.

Termination method had an effect on average weed control 51 DAP at Oakes (Table 3). Cover crop plots killed with an herbicide application or roto-tilled had greater weed control at 51 DAP compared with cover crop plots terminated with disk-tilling. Results suggest that even though all cover crops varied in biomass production, using a disk to terminate the plots distributed the biomass so that after the second cultivation, weed control was less than when an herbicide or roto-tiller was used to terminate the cover crops.

Table 3. Effect of termination method on average weed control 51 days after planting (DAP) averaged over cover crop, Oakes, ND, USA, 2010.

Termination Method	**Weed Control**
	% Control
Disk-till	89
Roto-till	94
Herbicide	93
LSD [z]	3

[z] Calculated to compare all levels of the termination method main effect according to Fisher's Protected LSD ($p \leqslant 0.05$).

Mowing the cover crops with a rotary mower to assist with potato planting procedures was thought to have influenced weed control. The rotary mower that was used visibly distributed the mowed cover crop residue unevenly; leaving a swath of residue running parallel with a swath of less residue in the direction the mower was operated, potentially lowering weed control. Dabney *et al.* [20] recognized that a rotary type mower could not mow as close to the ground as other mower types and Creamer and Dabney [24] identified that a flail mower provided the most uniform distribution of cover crop residue over the soil surface resulting in more uniform weed control. However, a flail mower was not available for this study and potato production involves more soil disturbance throughout the season than other crops which do not require cultivation. At planting, a hill is made to cover the seed with soil. Throughout the early part of the season, one or more mechanical cultivations for hilling ensures both adequate soil covering of tubers and weed control. In this research with the large amount of biomass from cover crops, it was unknown if the hilling at planting and subsequent cultivations would properly redistribute the cover crop residue. Weed control results from 14 to 51 DAP suggest that, in general, the non-uniform distribution of cover crop residue with the rotary mower did not negatively affect weed control unless a disk was used to kill the cover crop.

More weeds emerged per unit area for the triticale cover crop when disk-till was used to terminate compared with other cover crops and termination methods (Table 4). In contrast, the lowest weed densities occurred when rye was the cover crop and was terminated by roto-tilling or by herbicide, and when rye/canola was killed by roto-tilling. Allelopathy has been demonstrated on some weed species, specifically redroot pigweed, from both rye and turnip cover crop residues [8,25]. Results indicate that allelopathy assisted with weed control as triticale and rye had similar biomass production, but rye terminated by roto-tilling or herbicide has lower weed densities. Rye/canola cover crop had lower biomass compared with rye alone, but the improved mixing of the biomass and soil with the roto-tilling may have attributed to the lower weed density with this treatment combination.

Table 4. Effect of cover crop and termination method on average weed density pooled over three weed evaluation periods at Oakes, ND, USA, 2010.

	Cover Crop					
Termination Method	**Triticale**	**Rye**	**Turnip/Radish**	**Rye/Canola**	**No Cover Crop**	**Mean**
			no· $\mathbf{m^{-2}}$			
Disk-till	102	54	65	70	59	70
Roto-till	54	27	86	38	- [x]	51
Herbicide	43	32	86	59	75	59
Mean	66	38	79	56	67	
LSD_1 [z]			4			
LSD_2 [y]			3			

[z] LSD_1 was calculated to compare all levels of cover crop for the same termination method according to Fisher's Protected LSD ($p \leqslant 0.05$); [y] LSD_2 was calculated to compare all levels of termination method for the same cover crop method according to Fisher's Protected LSD ($p \leqslant 0.05$); [x] A no cover crop and no termination method was used as a check and a substitute for the factorial treatment combination of no cover crop and roto-till termination.

The interaction of cover crop and termination method were found to influence weed fresh weight when averaged over the three evaluation timings (Table 5). Even though the triticale cover crop with disk-till termination had the greatest average weed density, the no cover crop and roto-till termination method had the greatest weed fresh weight, indicating that the weeds were much larger and thus more competitive.

Cover crop and termination method affected weed control 13, 26, and 42 DAP at Carrington (data not shown). Though statistical significance existed, the overall weed control was high and a difference of a percent or two is not critical to the overall conclusions. At 13 DAP, all treatment combinations had 95% or greater average weed control with a range from 95% to 99%. At 26 DAP, all treatment combinations had 94% or greater average weed control with a range from 94% to 99%. Finally, at

42 DAP, all treatment combination had greater than 90% weed control with a range from 90% to 95%. The presence of a cover crop did not affect weed control above no cover crop as weed pressure was low for the entire trial. Weed density and fresh weight were not affected by cover crop or termination method (data not shown). The lack of differences was again attributed to the overall low weed pressure of the environment. This minimal weed pressure could have resulted from lack of timely rains for weed seed germination paired with timely cultivations to disturb the weed seed bed and cover germinated weed seeds.

Table 5. Effect of cover crop and termination method on average weed fresh weight pooled over three weed evaluation periods at Oakes, ND, USA, 2010.

	Cover Crop					
Termination Method	**Triticale**	**Rye**	**Turnip/Radish**	**Rye/Canola**	**No Cover Crop**	**Mean**
			$g \cdot m^{-2}$			
Disk-till	24.7	0.5	2.2	7.0	87.1	24.3
Roto-till	3.2	0.0	8.1	2.2	- [x]	7.0
Herbicide	0.0	1.6	0.0	18.3	4.3	4.8
Mean	9.3	0.7	3.4	9.2	45.7	
LSD_1 [z]			12.6			
LSD_2 [y]			9.8			

[z] LSD_1 was calculated to compare all levels of cover crop for the same termination method according to Fisher's Protected LSD ($p \leqslant 0.05$); [y] LSD_2 was calculated to compare all levels of termination method for the same cover crop method according to Fisher's Protected LSD ($p \leqslant 0.05$); [x] A no cover crop and no termination method was used as a check and a substitute for the factorial treatment combination of no cover crop and roto-till termination.

2.3. *Yield*

Potato cultivars did not differ in their responses to cover crops and termination methods and thus data were pooled over cultivars. Cover crop and termination method did not affect plant stand count at either location. Plant stand counts averaged 85% of the planted seed pieces over all cover crops and termination method treatments (data not shown). Seed pieces planted into cover crop residue greater than 5000 $kg \cdot ha^{-1}$ appeared to be shallower due to difficulties with the planting shovel opening the planting furrow, but this did not cause lower plant stands.

Total tuber yield paralleled marketable yield, thus discussion will focus on marketable yield. Termination method had an effect on marketable yield at Oakes (Table 6). When the seedbed was prepared with roto-tilling, marketable yields were 2–2.5 $Mg \cdot ha^{-1}$ higher than either disk-tilling or herbicide. Soil texture is coarse at Oakes, which made it difficult to plant the potato seed pieces at the recommended depth when roto-till was not used to terminate the cover crop. Roto-tilling the soil before planting produced the most uniform soil seed-bed, leading to greater potato marketable yield.

Table 6. Effect of termination method on marketable yield averaged over cover crop, Oakes, ND, USA, 2010.

Termination Method	**Marketable Yield**
	$Mg \cdot ha^{-1}$
Disk-till	22.6
Roto-till	24.6
Herbicide	22.1
LSD [z]	1.5

[z] Calculated to compare all levels of the cover crop main effect according to Fisher's Protected LSD ($p \leqslant 0.05$).

Tuber growth cracks, brown center, and hollow heart were evaluated for tuber quality, but no significant differences of the treatment factors or interactions was observed. This was expected since the incidence of these defects increases when growing conditions abruptly change during the season, such as when potato plants recover too quickly after a period of environmental or nutritional stress [26].

There were no main effects or interaction effects on marketable yield at Carrington (Tables 7 and 8). Glyphosate termination of cover crops and subsequent no-till planting having no effect on marketable yield is similar to what has been found in no-till production in NC and VA, USA, where no-till yields equaled conventional yields [16,19]. Previous research with cover crops in irrigated potato have found mixed yield responses. Essah *et al.* [27] found increased potato yields with sudangrass cover crops in Central Colorado compared to no cover crop in some environments.

Table 7. Effect of cover crop on marketable yield averaged over termination method, Carrington, ND, USA, 2011.

Cover Crop	Marketable Yield
	$Mg \cdot ha^{-1}$
Triticale	22.2
Rye	19.6
Hairy vetch	20.9
Rye/hairy vetch	22.6
No cover crop	25.1
LSD [z]	NS

[z] Calculated to compare all levels of the cover crop main effect according to Fisher's Protected LSD ($p \leqslant 0.05$).

Table 8. Effect of termination method on marketable yield averaged over cover crop, Carrington, ND, USA, 2011.

Termination Method	Marketable Yield
	$Mg \cdot ha^{-1}$
Disk-till	21.2
Roto-till	22.2
Herbicide	22.2
LSD [z]	NS

[z] Calculated to compare all levels of the termination method main effect according to Fisher's Protected LSD ($p \leqslant 0.05$).

Cover crop and termination method did not influence tuber hollow heart at Carrington (data not shown). However, sun-scald was prevalent, affecting 37% of tubers on average. Tuber sun-scald generally results from a poor hill structure that causes tubers to be exposed to the sun [12]. The percentage of sun-scald tubers did not vary with cover crop or termination method. Sun scald tubers may cause additional sorting of marketable tubers and even the rejection of the entire shipment decreasing profit for producers. Bellinder *et al.* [12] identified increased cultivation as the primary solution for tuber greening. However, the current study received three cultivations, thus disk cultivators may not be able to move soil above the tubers when cover crops are grown on fine-textured soils. Chitsaz and Nelson [11] recognized the importance of cultivation for successful potato production but also realized that cultivation depended on favorable weather conditions. Since cultivation timing was dictated by the experiment protocol, soil conditions may not have been optimal for the cultivator to move the soil to the top of the hill.

Selecting a cultivar that sets tubers deeper may have been able to overcome the tuber sunscald problem. Pavek and Thornton [28] showed that cultivars differ in the depth of tuber set within the hill and that shallower set tubers require larger hills to ensure no tuber greening. Additional research should examine if cultivars with a deeper tuber set would help to overcome the difficulties of seed piece placement and hilling on heavier soils when cover crops are used for weed control.

3. Experimental Section

3.1. Experimental Sites

Field experiments were conducted to evaluate weed control with cover crops in irrigated potato. Field experiments were conducted at the Oakes Research Extension Center (OREC), near Oakes, North Dakota (46.07 N, −98.09 W; elevation 392 m) in 2010. The experiment at Oakes was conducted on an Embden loam (coarse-loamy, mixed, superactive, frigid Pachic Hapludolls) and Gardena loam (coarse-silty, mixed, superactive, frigid Pachic Hapludolls), classified as a sandy loam soil texture. The experiment was repeated in 2011 at the Carrington Research Extension Center (CREC), near Carrington, North Dakota (47.51 N, −99.13 W; elevation 475 m). The experiment at Carrington was carried out on a Heimdal loam soil (coarse-loamy, mixed, superactive, frigid Calcic Hapludolls), classified as a silty loam soil texture.

3.2. Experimental Design and Treatments

The experimental design was a randomized complete block with a factorial arrangement and four replicates. Cover crop termination treatments were glyphosate, disk-till, and roto-till. Cover crop treatments were triticale, rye, hairy vetch, rye/hairy vetch, and no cover crop. Hairy vetch winter-kill during 2009 to 2010 resulted in the spring planting of turnip/radish and canola in place of hairy vetch. To include a check treatment, the combination of no cover crop and roto-till was excluded, with roto-till being substituted for no termination treatment. Potato cultivars "Russet Norkotah" and "Yukon Gold" were planted at both locations but considered a random effect and pooled together.

3.3. Management

3.3.1. General Management

Certified seed potatoes were cut into 57 g ± 14 g seed pieces that were stored at 16 °C with approximately 90% relative humidity for 2–7 days to allow for suberization before planting. Standard recommended grower practices were used for soil fertility, irrigation, and insect and disease management. Individual experimental units were 3.04 m wide by 7.62 m long with four rows of potatoes spaced 0.76 m apart. Triticale, rye, and hairy vetch were planted at 151.3 kg· ha^{-1}, 132.4 kg· ha^{-1}, and 33.6 kg· ha^{-1}, respectively, with a grain drill (Case International Harvester; Racine, WI, USA). In the combined planting, rye was planted at 65.4 kg· ha^{-1} and hairy vetch was planted at 33.6 kg· ha^{-1}. A burn-down herbicide application of glyphosate at 861.8 g ae/ha was applied approximately two weeks before potato planting. Cover crop biomass was harvested just before any cover crop mowing or tilling inside a 0.09 m^2 quadrat and dried at 40 °C for dry weight measurements. Each whole plot was mowed with a 1.5 m rotary mower (John Deere; Moline, IL, USA) prior to either tillage treatment. The roto-till treatment was performed with a 1.8 m roto-tiller (Woods; Oregon, IL, USA) while the disk-till treatment was performed with a 2.1 m disk (John Deere; Moline, IL, USA).

Potato seed pieces were planted with a two-row potato planter (Iron Age Co. (out of business); Glenoch, NJ, USA). A granular fertilizer, 32–10–10 (N, P, K) was banded in-furrow during potato planting at 160 kg N/ha, 50 kg P_2O_5/ha, and 50 kg K_2O/ha. Cultivation was conducted with a two-row disk cultivator (Harriston Industries; Minto, ND, USA) immediately after the weed evaluations. Two potato rows in each experimental unit were harvested with a single-row potato digger (US Small Farms; Torrington, WY, USA). Harvested tubers were graded in Fargo, ND with a single six station slide ejection photo sizer (Hagen Electronics; Reno, NV, USA). Tubers were separated into non-marketable (<113 g or visual defects) and marketable (>113 g) yields. Ten tubers from each plot were randomly selected for hollow heart and sun scald evaluation. Hollow heart was detected by slicing each potato in half and identifying the presence of a hollow center, while sun scald was measured by analyzing the halved potatoes for greening between the skin and inner flesh.

3.3.2. Oakes, 2010 Additional Management

The previous crop at Oakes in 2009 for half of the trial was spring wheat (*Triticum aestivum* L.) and the other half dry edible bean (*Phaseolus vulgaris* L.). A composite soil sample was taken from both the wheat and dry edible bean residue. In the 0–20 cm depth the wheat residue had 53 ppm NO_3-N, 23 ppm P, and 140 ppm K while the dry edible bean residue had 64 ppm NO_3-N, 18 ppm P, and 115 ppm K. There is a nitrogen credit given to the dry edible bean of 53 ppm NO_3-N. A spring granular fertilizer of 31.1 kg N/ha, 20.9 kg P_2O_5/ha, and 47.4 kg K_2O/ha was applied 6 April 2010 to replications 1 and 2 where the spring wheat was grown the previous year to compensate for soil testing differences in replications 3 and 4 that had a prior crop of dry edible bean. Due to the hairy vetch winter-kill, a turnip/radish combination and canola were spring planted by manual spreading and subsequent raking seed at 5.6 kg·ha^{-1} turnip, 5.6 kg·ha^{-1} radish, and 12.4 kg·ha^{-1} canola.

3.4. Weed Evaluations

Early-season weed control was estimated by weed species counts, weed above-ground fresh weights, and visual evaluations. Weed evaluations (weed counts, weed weights, and visual weed control ratings) were taken three times, approximately 14, 28, and 42 days after planting (Table 9). Weed counts were taken within a 0.09 m^2 quadrat randomly placed on top of a potato row. Weed fresh weights were taken immediately after weed counts. Visual weed control evaluations were taken using a rating scale of 0% to 100%, where 0 = no control and 100 = complete weed control, referenced to the alleyways of the research where no weed control existed.

Table 9. Description of field sites, selected management practices, and data collection.

	Oakes, 2010	**Carrington, 2011**
Cover crop planting	9/29/09, 4/16/10	8/26/11
Previous crop	Spring wheat and dry edible bean	Barley
Irrigation	Linear overhead	Center pivot overhead
Burn down herbicide	5/24/10	6/3/11
Cover crop harvest	6/1/10	6/15/11
Cover crop mowing	6/1/10	6/16/11
Cover crop tillage	6/1/10	6/16/11
Potato planting	6/2/10	6/16/11
Weed evaluations	6/16, 7/1, 7/23/10	6/29, 7/12, 7/28/11
Stand counts	8/3/10	7/28/11
Harvest	10/13/10	10/13/11

3.5. Statistical Analysis

The analysis of variance was conducted with the GLM procedure in SAS (SAS version 9.3, SAS Institute, SAS Circle, P.O. Box 8000, Cary, NC, USA) with an alpha level of 0.05 for all agronomic data. Transformation of weed control data did not improve homogeneity of variance; thus, analysis was performed on non-transformed data. Means were separated, where appropriate, using Fisher's protected LSD test at $p \leqslant 0.05$. Data from each location (Oakes and Carrington) were analyzed individually due to different treatments.

4. Conclusions

In conclusion, adequate weed control was obtained with the use of cover crops and hilling or cultivation at both field locations. Only the roto-tilled cover crop termination method influenced potato yield at Oakes due to the soil texture at this location. Potato production into cover crop residues presents significant mechanical challenges for cover crop desiccation, potato planting, and hill formation, which are far different from conventional potato production. Overall, cover crops could be integrated into an irrigated potato production system for weed control, if specific benefits from an alternative cropping system are sought.

Acknowledgments: We acknowledge the field assistance of James Loken, John Stenger, Andrew Aippersbach, and the technical support of Collin Auwarter. The study was in part funded by North Central Region Sustainable Agriculture and Education (NCR-SARE).

Author Contributions: Harlene Hatterman-Valenti was the advisor for Grant Mehring during his M.S. degree at North Dakota State University in the Department of Plant Sciences.

Conflicts of Interest: The authors declare no conflict of interest.

The following abbreviations are used in this manuscript:

Nomenclature

potato; *Solanum tuberosum*; triticale; x *Triticosecale*; rye; *Secale cereale* L.; hairy vetch; *Vicia villosa* Roth; turnip; *Brassica rapa* L.; radish; *Raphanus sativus* L.

References

1. Beukema, H.P.; van der Zaag, D.E. *Introduction to Potato Production*; Backhuys Publishers: Kerkwerve, The Netherlands, 1990.
2. Dabney, S.M.; Buehring, M.W.; Reginelli, D.B. Mechanical control of legume cover crops. In *Cover Crops for Clean Water*; Hargrove, W.L., Ed.; Soil and Water Conservation Society: Ankeny, IA, USA, 1991; pp. 146–147.
3. Duval, J. Cover cropping in potato production. 1997. Available online: http://eap.mcgill.ca/publications/EAP71.htm (accessed on 15 November 2015).
4. Snapp, S.S.; Swinton, S.M.; Labarta, R.; Mutch, D.; Black, J.R.; Leep, R.; Nyiraneza, J.; O'Neil, K. Evaluating cover crops for benefits, costs, and performance within cropping system niches. *Agron. J.* **2005**, *97*, 322–332.
5. Teasdale, J. Cover crops, smother plants, and weed management. In *Integrated Weed and Soil Management*; Hatfield, J.L., Buhler, D.D., Stewart, B.A., Eds.; Sleeping Bear Press: Chelsea, MI, USA, 1998; pp. 247–270.
6. Rosecrance, R.C.; McCarty, G.W.; Shelton, D.R.; Teasdale, J.R. Denitrification and N mineralization from hairy vetch (*Vicia villosa* Roth) and rye (*Secale cereal* L.) cover crop monocultures and bicultures. *Plant Soil* **2000**, *227*, 283–290. [CrossRef]
7. Justes, E.; Mary, B.; Nicolardot, B. Comparing the effectiveness of radish cover crop, oilseed rape volunteers and oilseed rape residues incorporation for reducing nitrate leaching. *Nutr. Cycl. Agroecosyst.* **1999**, *55*, 207–220. [CrossRef]
8. Petersen, J.; Belz, R.; Walker, F.; Hurle, K. Weed suppression by release of isothiocyanates from turnip-rape mulch. *Agron. J.* **2001**, *93*, 37–43. [CrossRef]
9. Nelson, D.C.; Thoreson, M.C. Competition between potatoes (*Solanum tuberosum*) and weeds. *Weed Sci.* **1981**, *29*, 672–677.
10. Nelson, D.C.; Giles, J.F. Weed management in two potato (*Solanum tuberosum* L.) cultivars using tillage and pendimethalin. *Weed Sci.* **1989**, *37*, 229–232.
11. Chitsaz, M.; Nelson, D.C. Comparison of various weed control programs for potatoes. *Am. Potato J.* **1983**, *60*, 271–280. [CrossRef]
12. Bellinder, R.R.; Wallace, R.W.; Wilkins, E.D. Reduced rates of herbicides following hilling controlled weeds in conventional and reduced tillage potatoes. *Weed Technol.* **1996**, *10*, 311–316.
13. Anonymous. Pesticide Use Statistics. National Agricultural Statistics Service. Available online: http://www.pestmanagement.info/nass/ (accessed on 15 November 2015).
14. Ackley, J.A.; Wilson, H.P.; Hines, T. Efficacy of rimsulfuron and metribuzin in potato (*Solanum tuberosum*). *Weed Technol.* **1996**, *10*, 475–480.
15. Heap, I. International Survey of Herbicide Resistant Weeds. 2011. Available online: http://www.weedscience.org/In.asp (accessed on 15 November 2015).
16. Morse, R.D. Using High-residue Cover Crop Mulch For Weed Management In Organic No-Till Potato Production Systems. 2006. Available online: http://ofrf.org/funded/reports/morse_03s18.pdf (accessed on 20 October 2015).

17. Conklin, A.E.; Erich, M.S.; Liebman, M.; Lambert, D.; Gallandt, E.R.; Halterman, W.A. Effects of red clover (*Trifolium pretense*) green manure and compost soil amendments on wild mustard (*Brassica Kaber*) growth and incidence of disease. *Plant Soil* **2002**, *238*, 245–256. [CrossRef]
18. Mohler, C.L.; Teasdale, J.R. Response of weed emergence to rate of *Vicia villosa* Roth and *Secale cereal* L. residue. *Weed Res.* **1993**, *33*, 487–499. [CrossRef]
19. Mundy, C.; Creamer, N.G.; Crozier, C.R.; Wilson, L.G.; Morse, R.D. Soil physical properties and potato yield in no-till, subsurface-till, and conventional-till systems. *HortTechnology* **1999**, *9*, 240–247.
20. Dabney, S.M.; Delgado, J.A.; Reeves, D.W. Using winter cover crops to improve soil and water quality. *Commun. Soil Sci. Plant Anal.* **2001**, *32*, 1221–1250. [CrossRef]
21. De Bruin, J.L.; Porter, P.M.; Jordan, N.R. Use of rye cover crop following corn in rotation with soybean in the Upper Midwest. *Agron. J.* **2005**, *97*, 587–598. [CrossRef]
22. Maul, J.; Mirsky, S.; Emche, S.; Devine, T. Evaluating a germplasm collection of the cover crop hairy vetch for use in sustainable farming systems. *Crop Sci.* **2011**, *5*, 2615–2625. [CrossRef]
23. Moore, M.J.; Gillespie, T.J.; Swanton, C.J. Effect of cover crop mulches on weed emergence, weed biomass, and soybean (Glycine max) development. *Weed Technol.* **1994**, *8*, 512–518.
24. Creamer, N.G.; Dabney, S.M. Terminating cover crops mechanically: Review of recent literature and assessment of new research results. *Am. J. Altern. Agric.* **2002**, *17*, 32–40.
25. Putnam, A.R.; Defrank, J.; Barnes, J P. Exploitation of allelopathy for weed control in annual and perennial cropping systems. *J. Chem. Ecol.* **1983**, *9*, 1001–1010. [CrossRef] [PubMed]
26. Identifying Potato Diseases in Pennsylvania. Available online: http://pubs.cas.psu.edu/FreePubs/pdfs/agrs75.pdf (accessed on 30 October 2015).
27. Essah, Y.C.; Delgado, J.A.; Dillon, M.; Sparks, R. Cover Crops Can Improve Potato Tuber Yield and Quality. *HortTechnology* **2012**, *22*, 185–190.
28. Pavek, M.; Thornton, R. Planting depth influences potato plant morphology and economic value. *Am. J. Potato Res.* **2009**, *86*, 56–67. [CrossRef]