Strip Tillage and Early-Season Broadleaf Weed Control in Seeded Onion (*Allium cepa*)

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Abstract: Field experiments were conducted in 2007 and 2008 near Oakes, North Dakota (ND), USA, to evaluate if strip tillage could be incorporated into a production system of seeded onion (*Allium cepa*) to eliminate the standard use of a barley (*Hordeum vulgare*) companion crop with conventional, full width tillage, yet support common early-season weed control programs. A split-factor design was used with tillage (conventional and strip tillage) as the main plot and herbicide treatments (bromoxynil, DCPA, oxyfluorfen, and pendimethalin) as sub-plots. Neither tillage nor herbicide treatments affected onion stand counts. Common lambsquarters (*Chenopodium album*) densities were lower in strip tillage compared to conventional tillage up to three weeks after the post-emergence applied herbicides. In general, micro-rate post-emergence herbicide treatments provided greater early-season broadleaf weed control than pre-emergence herbicide treatments. Onion yield and grade did not differ among herbicide treatments because the mid-season herbicide application provided sufficient control/suppression of the early-season weed escapes that these initial weed escapes did not impact onion yield or bulb diameter. In 2007, onion in the strip tillage treatment were larger in diameter resulting in greater total and marketable yields compared to conventional tillage. Marketable onion yield was 82.1 Mg ha^{-1} in strip tillage and 64.9 Mg ha^{-1} in conventional tillage. Results indicate that strip tillage use in direct-seeded onion production was beneficial, especially when growing conditions were conducive to higher yields and that the use of strip tillage in onion may provide an alternative to using a companion crop as it did not interfere with either early-season weed management system.

Keywords: common lambsquarters (*Chenopodium album*); redroot pigweed (*Amaranthus retroflexus*); hairy nightshade (*Solanum physalifolium*); herbicide reduced rates; reduced tillage

1. Introduction

Onion (*Allium cepa*) is the fifth most-valuable vegetable crop produced and the third largest fresh vegetable industry in the United States with an annual crop value of almost one billion dollars direct from the field [1,2]. It is an intensively managed crop characterized by slow emergence, poor competitive morphology, and limited early-season weed management options, which means that yields can fall within a wide range depending on the cultivation conditions and the degree of weed control [3,4]. When seed are sown directly into the ground a well-prepared field is required as any stress to onion can negatively affect bulbing and yield [5]. Other factors that may influence onion yield and quality include planting date, plant spacing, soil moisture, and damage from blowing soil, insects, or diseases.

High winds in North Dakota may remove seed from the rows or damage newly emerged onion seedlings [6]. To reduce damage to onion from blowing soil particles, growers plant barley (*Hordeum vulgare*) as a companion crop. Barley emerges quickly in comparison to onion, but this also

complicates weed management strategies since growers do not want to reduce barley germination, but must kill the barley before it reaches a height of 18 cm and competes with the onion crop reducing onion yield [7].

In a reduced tillage system or a low disturbance tillage system at least 30% of the soil surface remains covered by residue compared to conventional, full-width tillage [8]. Strip tillage is a form of conservation tillage, which disturbs only the crop rows while the rest of the soil remains undisturbed. As a result, soil losses by wind and water erosion are reduced by 25% to 30%. Residue on the soil surface may also reduce weed seedling emergence by allelopathic and shading effects or by intercepting herbicide applications [9]. Strip tillage is an emerging practice in vegetable production as it offers advantages of less erosion and maintained soil quality compared with conventional tillage [10].

Weed control is a vital component in the production of marketable onion. However, herbicide application restrictions and limited weed control spectra with pre-emergence herbicides (PRE) make early-season broadleaf weed control in seeded onion difficult. This is further complicated when a barley companion crop is planted as previously described. Recent research has shown effective early-season broadleaf weed control can be achieved by applying post-emergence (POST) herbicides at regular intervals as micro-rates when broadleaf weeds are in the cotyledon to first-true-leaf stage [11]. These applications have been effective in standard tillage systems, but have not been tested in strip tillage systems. The objective of this research was to determine if strip tillage could be used instead of standard tillage practices in seeded onion when various early-season (prior to onion two-leaf growth stage) weed control options were used.

2. Materials and Methods

Field experiments were conducted at the Oakes Research Extension Center near Oakes, ND, in 2007 on an Embden loam and in 2008 on a Hecla sandy loam with a previous crop of hard red spring wheat (*Triticum aestivum*) each year. A split-factor design was used with tillage as the main plot and herbicide treatments as sub-plots, replicated four times. Individual plots were four paired-rows of 'Teton' (Petoseed Co., Santa Maria, CA, USA) onion with main rows measuring 40.6 cm from center-to-center and 6.4 cm between each pair.

2.1. Tillage and Herbicide Treatments

Conventional and strip tillage treatments were conducted 15 October 2007 and 13 October 2008. Conventional or non-inversion tillage consisted of two passes of a field cultivator that disturbed the soil to an average depth of 30 cm. In 2008, the conventional tillage treatment required an additional field cultivator pass 21 April to reduce soil clods and create a suitable seedbed. Strips for the strip tillage treatment were made using a strip tiller (Maverick; Yetter Manufacturing Inc., Colchester, IL, USA) equipped with coulters. Strips were 15.2 cm wide and tilled to a depth of 15 to 20 cm.

Herbicide treatments included PRE herbicides DCPA (Dacthal W-75; AMVAC Chemical Corporation, Los Angeles, CA, USA) or pendimethalin (Prowl H_2O; BASF Corporation, Research Triangle Park, NC, USA) and POST herbicides bromoxynil (Buctril; Bayer CropScience, Research Triangle Park, NC, USA) or oxyfluorfen (GoalTender; Dow AgroSciences, Indianapolis, IN, USA). For comparison two checks: the standard grower practice for weed control and a hand-weeded check were included. The standard grower practice for weed control consisted of DCPA applied PRE at 11.2 kg ai ha^{-1}. Weekly hand-weeding began once the onion row could be seen. The other DCPA treatment examined the lowest herbicide rate on the label. DCPA and pendimethalin were applied one week after planting at 8.4 kg ha^{-1} and 0.8 kg ai ha^{-1}, respectively. POST herbicides were applied at micro-rates, which consisted of four weekly applications at 70.1 g ha^{-1}, which corresponded to 0.25 and 0.5 times the lowest labeled rate for bromoxynil and oxyfluorfen, respectively. Micro-rate applications began when broadleaf weeds reached the cotyledon to one-true-leaf stage, which corresponded to the loop-stage for onion both years. An overview of the herbicide treatments and timings are shown in Table 1. A CO_2-pressurized backpack sprayer was used to make all micro-rate treatment applications.

The backpack sprayer was equipped with TeeJet 8002 flat-fan nozzles (Spraying Systems Co., Chicago, IL, USA) spaced at 45.7 cm along a 1.5-m-wide boom, which sprayed four paired-rows at a time and was calibrated to deliver 187 L ha^{-1}.

Table 1. Pre- and post-emergence herbicide application rates and timings at Oakes, ND, USA in 2007 and 2008.

Treatment	Rate	Date of Application			
		1	**2**	**3**	**4**
Oakes 2007	g ai ha^{-1}				
Pre-emergence					
DCPA	8405	30 April			
Pendimethalin	798.6	30 April			
Post-emergence					
Bromoxynil	70.1	16 May	23 May	31 May	6 June
Oxyfluorfen	70.1	16 May	23 May	31 May	6 June
Oakes 2008					
Pre-emergence					
DCPA	8405	1 May			
Pendimethalin	798.6	1 May			
Post-emergence					
Bromoxynil	70.1	16 May	26 May	3 June	9 June
Oxyfluorfen	70.1	16 May	26 May	3 June	9 June

2.2. General Procedures

Onion were seeded at a population of 617,760 and 704,250 seeds/ha on 20 April 2007 and 23 April 2008, respectively and grown in accordance to production recommendations, including soil fertility, overhead irrigation, as well as insect and disease management practices [12]. Five in-season nitrogen applications (32% urea-ammonium nitrate) were applied at 2 weeks intervals, beginning at the onion three-leaf growth stage. During the 2007 growing season, the fungal leaf disease purple blotch (causal agent, *Alternaria porri*) was detected and controlled with applications of the fungicides azoxystrobin (Quadris; Syngenta Crop Protection LLC, Greensboro, NC, USA) at 146 g ai ha^{-1} and pyraclostrobin (Headline; BASF Corporation, Research Triangle Park, NC, USA) at 219 g ai ha^{-1} in rotation. Onion fly maggots (*Delia antique*) were also detected in 2007 and were controlled with chlorpyrifos (Lorsban; Dow AgroSciences, Indianapolis, IN, USA) at 1120 g ai ha^{-1}. In 2008, fungicide applications of azoxystrobin (146 g ha^{-1}) and pyraclostrobin (219 g ha^{-1}) were made in rotation, similar to that denoted for 2007.

Grass weeds were controlled as needed with clethodim (Select; Valent USA Corp, Walnut Creek, CA, USA) at 140 g ai ha^{-1} plus a crop oil concentrate (Herbimax; Loveland Products Inc, Greeley, CO, USA) at 1% *v/v*. All treatments received a POST application of bromoxynil and oxyfluorfen at 280 g ha^{-1}, and 1120 g ha^{-1}, respectively, at the onion two- to three-leaf growth stage for mid-season weed control. If onion in the POST herbicide treatments reached the two- to three-leaf growth stage before micro-rate applications were completed, the mid-season application was delayed one week after the last micro-rate application. This occurred in 2007. Fertilizer, fungicide, and standard herbicide applications were made with a tractor mounted sprayer equipped with TeeJet 8002 flat-fan nozzles, spaced at 48 cm along a 2.8-m-wide boom; the sprayer was calibrated to deliver 170 L ha^{-1}.

Three broadleaf weed species, common lambsquarters (*Chenopodium album*), redroot pigweed (*Amaranthus retroflexus*), and hairy nightshade (*Solanum physalifolium*) were evaluated. Broadleaf weed control was evaluated by counting plants within a 1 m^2 quadrate in the onion row 7 d after each micro-rate herbicide application, but prior to the sequential application.

Onion bulbs were hand harvested, allowed to cure, and then graded according to the United States Department of Agriculture's (USDA) standards as cull, small, medium, and large [13]. Bulbs were harvested from each middle two paired-rows on 5 September 2007 and 24 September 2008; harvested area was equal to 2.5 m^2. The USDA standard diameters of grades were: cull, less than

2.5 cm; small, 2.5 cm to 5.7 cm; medium, 5.7 cm to 7.6 cm; and large, greater than 7.6 cm. Split and diseased bulbs were graded as culls, regardless of diameter.

2.3. Statistical Analysis

Data were statistically analyzed using two-way analysis of variance using the Mixed Procedure of SAS (version 9.1.3, SAS Institute Inc., Cary, NC, USA) with an alpha value of 0.05. Each environment was analyzed separately to test for homogeneity of mean square errors; environments were combined and analyzed when appropriate. The hand-weeded check was not included with the statistical analysis because onion were injured during the weed removal process and resulted in low yields. In the past, hand-weeding was initiated prior to onion emergence and hypothesized that this procedure reduced yield [14]. Low onion yield, regardless of when hand-weeding was initiated, indicated the difficulty of using hand-weeding for weed control in direct-seeded onion.

3. Results and Discussion

3.1. Onion Emergence

There was no tillage by herbicide interaction or differences between tillage or herbicide treatments for onion stand counts. This was expected as the onion double-rows were within similar soil conditions for the two tillage treatments. Pendimethalin has PRE application restrictions, especially if cool, rainy weather is expected, but has been shown to be very safe on onion in all types of situations when label restrictions are followed [15].

3.2. Common Lambsquarters Control

There was no tillage by herbicide interaction on common lambsquarters density for the first three weeks of evaluation. However, fewer common lambsquarters were associated with strip tillage (6 plants m^{-1}) compared to conventional tillage (11 plants m^{-1}) at one week after the first micro-rate herbicide application (data not shown). Crop residue remaining on the soil surface in strip-tilled plots may have reduced weed seed germination and emergence. Crop residue has been shown to shade weed seeds, inhibiting germination [16]. It has also been shown that reduced soil disturbance in strip tillage systems increased mortality of common lambsquarters seeds via predation and desiccation [9].

Herbicide efficacy differed among years for common lambsquarters at one week after the second micro-rate herbicide application (1WA2A) and one week after the third micro-rate herbicide application (1WA3A) (Table 2). During 2007, pendimethalin was not as effective at controlling common lambsquarters 1WA2A and 1WA3A compared to the other herbicide treatments. Clough and Ball [17] reported that a PRE herbicide application of DCPA was more effective for early control of common lambsquarters than pendimethalin in dry bulb onion production. In addition, POST herbicides at 1WA3A provided better common lambsquarters control than pendimethalin and DCPA, and similar common lambsquarters control as the standard herbicide. The POST herbicide (oxyfluorfen and bromoxynil) controlled successive common lambsquarters flushes due to the second and third application timing. The common lambsquarters population was low in 2008 and thus densities did not differ among herbicide treatments.

One week after the fourth micro-rate herbicide application (1WA4A), there was an interaction between herbicide and tillage for common lambsquarters densities (Table 3). More common lambsquarters plants were in the conventional tillage plots treated with oxyfluorfen than any other tillage and herbicide treatment combination. Greater common lambsquarters control was expected with bromoxynil compared to oxyfluorfen as common lambsquarters is listed as a most susceptible broadleaf weed species on the bromoxynil label [18]. In 2007, PRE treatments received the standard mid-season herbicide application when POST treatments received their fourth micro-rate application, since onion reached the leaf-stage for the mid-season tank-mix. Thus, most of the common lambsquarters that

escaped the PRE herbicide treatments (Table 2) were controlled, while later emerging common lambsquarters in the conventional tillage treatment were not controlled by oxyfluorfen.

Table 2. Common lambsquarters (*Chenopodium album*), redroot pigweed (*Amaranthus retroflexus*), and hairy nightshade (*Solanum physalifolium*) densities following herbicide applications at Oakes, ND, USA, during 2007 and 2008.

Treatment	Common Lambsquarters		Redroot Pigweed		Hairy Nightshade	
	2007	2008	2007	2008	2007	2008
	— plants·m^{-2} —		— plants·m^{-2} —		— plants·m^{-2} —	
1WA1A [z]						
Pendimethalin	14 a[x]	8 a	23 a	0 a	135 a	37 b
DCPA	4 b	14 a	19 a	0 a	110 a	75 a
Oxyfluorfen	4 b	20 a	1 b	0 a	19 b	12 c
Bromoxynil	0 b	6 a	1 b	0 a	18 b	20 bc
Grower Standard [y]	8 b	5 a	27 a	0 a	113 a	54 ab
1WA2A						
Pendimethalin	11 a	0 a	26 a	0 b	100 a	53 b
DCPA	7 ab	0 a	15 a	3 b	50 b	132 a
Oxyfluorfen	0 b	0 a	0 b	35 a	0 c	4 b
Bromoxynil	0 b	0 a	0 b	27 ab	3 c	11 b
Grower Standard	8 ab	0 a	22 a	0 b	35 b	126 a
1WA3A						
Pendimethalin	14 a	1 a	42 a	0 a	86 a	41 bc
DCPA	3 a	1 a	22 a	0 a	73 a	116 a
Oxyfluorfen	3 a	12 a	0 b	0 a	1 b	0 c
Bromoxynil	0 a	7 a	0 b	0 a	0 b	3 c
Grower Standard	3 a	0 a	35 a	0 a	73 a	97 ab
1WA4A						
Pendimethalin	1 a	1 a	3 a	0 a	0 a	33 b
DCPA	0 a	0 a	1 a	0 a	0 a	50 ab
Oxyfluorfen	3 a	15 a	0 a	0 a	1 a	0 c
Bromoxynil	0 a	4 a	0 a	0 a	1 a	0 c
Grower Standard	0 a	0 a	3 a	0 a	0 a	54 a

[z] 1WA1A = one week after first micro-rate herbicide application, 1WA2A = one week after second micro-rate herbicide application, 1WA3A = one week after third micro-rate herbicide application, 1WA4A = one week after fourth micro-rate herbicide application; [y] Standard grower practice of herbicide weed management, DCPA (PRE) followed by a POST application at onion three-leaf growth stage of bromoxynil and oxyfluorfen; [x] Means for each application timing and year followed by the same lower case letter are not significantly different according to Fisher's Protected LSD ($p < 0.05$).

Table 3. Common lambsquarters (*Chenopodium album*) and hairy nightshade (*Solanum physalifolium*) densities as affected by herbicide and tillage averaged over years at Oakes, ND, USA.

Herbicide	Common Lambsquarters [z]		Hairy Nightshade [y]	
	Strip Tillage	Conventional	Strip Tillage	Conventional
	——— (plants m^{-2}) ———		——— (plants m^{-2}) ———	
Pendimethalin	0 b [x]	3 b	43 bcd	128 a
DCPA	0 b	0 b	92 ab	94 ab
Oxyfluorfen	4 b	14 a	12 e	19 cde
Bromoxynil	3 b	1 b	16 de	22 c
Std. herbicide	0 b	0 b	52 bcd	77 abc

[z] Plant densities one week after fourth micro-rate herbicide application; [y] Plant densities one week after first micro-rate herbicide application; [x] Means for each weed species followed by the same lower case letter are not significantly different according to Fisher's Protected LSD ($p \leqslant 0.05$).

3.3. Redroot Pigweed Control

There was no tillage by herbicide interaction on redroot pigweed density for the four weeks of evaluation. Herbicide efficacy differed among years for redroot pigweed (Table 2). During 2007, POST herbicide treatments decreased redroot pigweed densities 1WA1A, 1WA2A, and 1WA3A in comparison to PRE herbicide treatments. Reduced redroot pigweed control with PRE herbicides in 2007 was attributed to a rainfall event five days following application. The PRE herbicides were applied on 30 April and 15 cm of rain fell over a two day period starting 4 May, which may have caused more herbicide to be lost through the soil profile [19].

Redroot pigweed densities in 2008 were minimal 1WA1A compared to the previous year. However, a flush of redroot pigweed emerged 1WA2A. At this time, similar redroot pigweed densities occurred in both POST herbicide treatments; however, redroot pigweed control was less with oxyfluorfen compared to the other herbicide treatments (Table 2). This flush was controlled with the third POST micro-rate herbicide application and redroot pigweed was not observed 1WA3A.

3.4. Hairy Nightshade Control

Hairy nightshade density varied among herbicide and tillage combinations only at 1WA1A (Table 3). Hairy nightshade density was lower when oxyfluorfen and bromoxynil were applied in either strip tillage or conventional tillage in comparison to DCPA or pendimethalin. However, when strip tillage was used, the highest plant density occurred where pendimethalin was applied, while under conventional tillage, the highest plant density was when DCPA was applied. Spring tillage practices have been shown to initiate hairy nightshade germination and increase emergence [20]. They found at least an 88% reduction in hairy nightshade populations when spring tillage was eliminated, suggesting that reduced tillage systems may reduce hairy nightshade pressure.

Herbicide efficacy differed among years for hairy nightshade evaluations 1WA2A and 1WA4A (Table 2). During 2007, hairy nightshade densities at 1WA2A were lowest in POST herbicide treated plots and greatest in PRE herbicide treated plots. No successive flushes of hairy nightshade occurred following 1WA2A. A similar pattern was seen during the 2008 growing season; namely, hairy nightshade densities were lower in POST herbicide treatments. Ransom *et al.* [21] reported more effective nightshade control in onion with PRE pendimethalin than DCPA. However, this contradicted the 2007 results where nightshade was more effectively controlled with DCPA than pendimethalin. The inconsistency of data from 2007 to 2008 was attributed to poor hairy nightshade control by either herbicide. Smith *et al.* [22] reported that both herbicides provided only partial hairy nightshade control in onion.

At 1WA4A in 2007, the mid-season herbicide application occurred the previous week for the PRE treatments, thus all herbicide treatments had similar hairy nightshade densities (Table 2). However, in 2008, hairy nightshade densities were lowest in POST herbicide treated plots and similar to results reported at 1WA2A.

3.5. Onion Yield

Results of homogeneity of error mean squares tests allowed for combined data analysis across growing seasons, but because the interaction between tillage and year was significant, discussion of growing seasons will remain separated. There was no tillage by herbicide interaction for onion grade and yield. Onion grade and yield did not differ among herbicide treatments during either growing season (data not shown). In 2007, most of the weeds that escaped the early-season herbicide treatments were either controlled or defoliated by the mid-season bromoxynil and oxyfluorfen tank-mix application, while in 2008; weed densities were low, especially for common lambsquarters and fewer weeds escaped the herbicide treatments and were controlled with the mid-season herbicide application. In both cases, those individuals that remained in the plots did not impact bulb diameter or overall yield. The lack of onion grade and yield differences among herbicide treatments suggests that even

though the post-emergence herbicide treatments generally provided better early-season broadleaf control compared to the pre-emergence treatments, this did not compensate for the additional costs associated with multiple spray applications and the increased weather risk associated with the need for four timely spray applications. The lack of onion grand and yield differences among herbicide treatments were contrary to those reported by Loken and Hatterman-Valenti [11], but do reinforce the importance of weed control at the onion two- and three-leaf stage (mid-season herbicide application) and prior to the onion bulbing stage.

In 2007, tillage affected onion yield as well as bulb diameter (Table 4). More large onion bulbs were produced under strip tillage compared to conventional tillage. This resulted in greater marketable and total yields compared to conventional tillage. Similar trends were also observed in 2008; however, the differences were not significant. There were more small-diameter onion with conventional tillage, but this did not influence marketable or total yields. Evans *et al.* [23] reported a 17% greater sugarbeet (*Beta vulgaris* L.) yield in only one year with strip tillage, which they attributed the standing straw stubble that protected sugarbeet seedlings from blowing soil during a spring wind storm. Haramoto and Brainard [24] reported that in row soil moisture was higher season-long in strip tillage compared with conventional tillage, but that tillage did not influence cabbage marketable yield. However, the cabbage were transplanted and thus less sensitive to soil moisture differences than a seeded crop. Both factors (reduced wind erosion and increased soil moisture) may have contributed to the increased onion yield with strip tillage, but it is more likely that the higher onion yield was a result of an increase in soil moisture with strip tillage [5].

Table 4. Onion (*Allium cepa*) grade and yield as affected by tillage and year averaged over herbicide treatments at Oakes, ND, USA.

Year	Onion Yield [z]				
	Small	Medium	Large	Marketable	Total
2007	────────		(Mg ha^{-1})		────────
Strip tillage	10.8 a [y]	32.8 a	49.3 a	82.1 a	92.9 a
Conventional	14.6 a	33.1 a	31.9 b	64.9 b	79.2 b
2008					
Strip tillage	7.6 b	25.6 a	25.3 a	50.8 a	58.4 a
Conventional	10.2 a	24.6 a	22.1 a	46.7 a	56.9 a

[z] Small = onion bulb diameter 2.5 cm to 5.7 cm, medium = onion bulb diameter 5.7 cm to 7.6 cm, large = onion bulb diameter greater than 7.6 cm, marketable = onion bulb diameter ⩾5.7 cm and not split or diseased; [y] Means within each column and year followed by the same letter are not significantly different according to Fisher's Protected LSD ($p ⩽ 0.05$).

4. Conclusions

There were no differences between tillage or herbicide treatments for onion stand counts. Post-emergence herbicides generally provided greater early-season common lambsquarters, redroot pigweed, and hairy nightshade control than pre-emergence herbicide treatments, but the greater early-season broadleaf weed control from multiple spray applications did not increase onion grade or yield. More large onion bulbs were produced under strip tillage compared to conventional tillage in 2007. This resulted in greater marketable and total yields under strip tillage compared to conventional tillage. Results support implementing strip tillage in seeded onion production, especially when growing conditions are conducive to higher yields. The use of strip tillage in onion production may provide an alternative to using a barley companion crop since onion can be readily planted within the tilled strip and crop residue remains undisturbed on more than half the area to reduce wind erosion. In addition, the use of strip tillage did not interfere with either PRE or POST herbicide systems used to provide early-season broadleaf weed control.

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