Effects of Strip Tillage and Irrigation Rate on Sugar Beet Crop Yield and Incidence of Insect Pests, Weeds, and Plant Pathogens

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ABSTRACT

Despite the many agronomic benefits of conservation tillage, little is known regarding the effects of reduced tillage on the pest complex in sugar beet. We examined the effects of two types of tillage (strip till versus conventional) and different irrigation rates on yield as well as densities of insect pests, weeds, and a soil-borne plant pathogen in sugar beet. Yields were similar between tillage treatments for two of the three years, but were greater for conventional tillage during one year in which a wet spring may have slowed seedling development in strip-tilled plots. The low irrigation treatment exhibited lower yields in one of three years, regardless of tillage treatment. Eggs of beet leafminer flies were more abundant in conventional tillage on three of eight observation dates, but larval densities did not differ by tillage treatment. Bean aphid incidences generally were positively related to irrigation rate. Total weed counts within beet rows did not

differ by tillage or irrigation, but between-row counts were greater for the high irrigation treatment during two years. Area under the disease progress curve for Rhizoctonia crown and root rot was higher in conventional tillage during one year. The results presented here show that strip-till sugar beet can be produced with yields comparable to conventional tillage without compromising pest management programs.

Additional Key words: conservation tillage; *Pegomya betae; Aphis fabae; Chenopodium album; Setaria viridis; Rhizoctonia solani;* evapotranspiration

INTRODUCTION

Strip tillage is a form of conservation tillage in which tillage is limited to a narrow band and a shallow depth, leaving some crop residue between the tilled strips undisturbed (Overstreet, 2009; Evans et al., 2010). The practicality of strip tillage has been enhanced by recent advances in strip-till equipment and development of technologies that improve weed management, such as glyphosate-resistant crops (Evans et al., 2010). These factors especially have led to increased interest in strip tillage production of sugar beet (*Beta vulgaris* L.). In addition, many agronomic benefits are associated with strip tillage, including reduced fuel and labor costs, reduced erosion, increased water retention and water use efficiency, and improved nutrient use (Sojka et al., 1980; Deibert, 1983; Aase and Pikul, 1995; Hatfield et al., 2001; Miyazawa et al., 2004; Licht and Al-Kaisi, 2005; Overstreet, 2009; Evans et al., 2010). Moreover, conservation tillage practices in sugar beet have been found to produce tonnage and sugar yields that are comparable to conventional tillage (Halvorson and Hartman, 1984; Miyazawa et al., 2004; Overstreet, 2009; Evans et al., 2010; Stevens et al., 2010; Tarkalson et al., 2012).

Despite the strong and growing interest in reduced tillage sugar beet production from agronomic and economic standpoints, limited research has focused on pest responses to conservation tillage in sugar beet agroecosystems. Across a variety of cropping systems, arthropod pest densities and/or damage may be increased, decreased, or equivocal when compared between conservation and conventional tillage practices (Brust et al., 1985; Hammond and Stinner, 1987; Stinner and House, 1990; Clark et al., 1994; Heimbach and Garbe, 1996; Gencsoylu and Yalcin, 2004; Bressan, 2009). Studies in Europe showed that conservation tillage in sugar beet may reduce densities of two aphids (Hemiptera: Aphididae), *Myzus persicae* (Sulzer) and *Aphis fabae* Scopoli, and a plant hopper, *Pentastiridius leporinus* (L.) (Hemiptera: Cixiidae) and may also reduce crop damage associated with these pests (Heimbach and Garbe, 1996; Bressan, 2009). Similar studies on pestiferous arthropods in the

US are lacking. The predicted effects of reduced tillage on a given insect pest depend in part upon the insect's biology. The reduced soil disturbance associated with conservation tillage provides a more stable environment for soil- and litter-dwelling arthropods and can reduce soil and near-surface temperature and moisture extremes (All and Gallaher, 1976; Stinner and House, 1990; Tonhasca and Stinner, 1991). Foliar insect pests may be expected to be affected less directly by reduced tillage, though their responses could be mediated through any changes in host plant physiology or quality (Price, 1991; Powell et al., 2006; Rousselin et al., 2016) that may be related to tillage practices.

Weeds may reduce sugar beet growth by outcompeting the crop for nutrients, water, and light (Schweizer and May, 1993). Sugar beet is particularly vulnerable to such competition because of its slow canopy closure and low plant height (Scott and Wilcockson, 1976). Conservation tillage practices have numerous effects on weeds, specifically on their distribution within the soil, ability to germinate, vulnerability to predation, and ability to grow (reviewed in Nichols et al., 2015). Conservation tillage also has impacts on herbicide activity. For example, conservation tillage can reduce herbicide leaching into the soil (Alletto et al., 2012). Moreover, higher levels of crop residues on the soil surface associated with conservation tillage may negatively affect herbicide efficacy by physically protecting weed seedlings from herbicide contact (Locke and Bryson, 1997; Alletto et al., 2010); however, the effects are not always consistent (Chauhan et al., 2006). Reduced tillage practices, including direct seeding, have been shown to reduce herbicide efficacy in some agricultural systems (Singh et al., 2015), but not in others (Hajebi et al., 2016). Weed management dynamics are more complicated in strip tillage than in direct seed systems because of the presence of tilled and untilled zones; therefore, a combination of practices may be necessary to control weeds in these systems (Brainard et al., 2013). More work is needed to clarify the effects of strip tillage on weed management in sugar beet.

By reducing the amount of soil turnover, conservation tillage tends to lead to the accumulation of organic material near the surface of the soil, favoring the development of a microbial environment that may either promote or reduce disease in plants (Sturz et al., 1997). For example, in wheat the pathogen that causes tan spot is favored by conservation tillage because it can survive in the residue left behind, whereas some root rot agents are reduced under conservation tillage because the increased soil moisture that the practice provides makes the plants less susceptible to the disease (Bockus and Shroyer, 1998). In sugar beet, fungal pathogens are the largest factor contributing to production losses (Oerke and Dehne, 2004). It is expected that the severity of soil-borne pathogens such as *Rhizoctonia solani*, *Aphanomyces cochlioides*, and *Polymyxa betae* (vector of *Beet necrotic yellow vein virus*) will increase with reduced tillage (Bockus and Shroyer, 1998). Sumner et al. (1986) found higher *R. solani* populations with reduced tillage following certain vegetable crops, and Buhre et al. (2009) showed that altering the cultivation method (plowing versus cultivating) can affect *R. solani* severity. However, Strausbaugh and Eujayl (2012) suggested that the *Rhizoctonia* / bacterial root rot complex in sugar beet did not differ between strip- and conventional tillage, but otherwise little is known about the effects of conservation tillage on soil-borne plant pathogens in sugar beet. *Cercospora*, a foliar pathogen, exhibited lower survival in sugar beet when the crop residue was buried (Khan et al., 2008), suggesting deep tillage may be necessary to bury the inoculum (Skaracis et al., 2010).

With widespread adoption of glyphosate-resistant sugar beet in North America, the use of strip tillage systems in sugar beet has become a more practicable option. Although conservation tillage has been widely studied in sugar beet, research has been lacking on the effects of reduced tillage in sugar beet on its complex of pests (including insects, weeds, and plant pathogens). Here we compared conventionally versus strip-tilled sugar beet with respect to yield parameters as well as the density, abundance, and/or incidence of insect pests, weeds, and a soil-borne plant pathogen.

MATERIALS AND METHODS

Field sites

We conducted this study at the University of Idaho Kimberly Research and Extension Center, Kimberly, ID, USA during the 2010 (42.551227 latitude, -114.340376 longitude), 2011 (42.549401, -114.348139), and 2012 (42.551292, -114.339094) growing seasons. The study area used each year had a cereal grain (wheat or barley) the previous year. The previous grain crop was harvested during the fall and standing stubble was cut to a height of 20-25 cm. We applied fertilizer by shanking into soil (strip-till plots) or by broadcasting (conventionally tilled plots) using a rate recommended by The Amalgamated Sugar Company: 3 kg N Mg^{-1} sugar beet roots with a yield goal of 78 Mg ha^{-1} (The Amalgamated Sugar Company, 2015). Strip-tillage plots were tilled using a four-row strip-till machine (Orthman Manufacturing, Inc., Lexington, NE, USA) which tilled bands ca. 18 cm wide at a depth of 15-18 cm. UAN liquid fertilizer (a mixture of urea and ammonium nitrate; 32-0-0) was injected into soil 5 cm below and 5 cm to one side of the seed. The strip-till implement was run through the entire length of the field, including through conventionally tilled plots; however, fertilizer was applied only while the implement was running through strip-till plots. Following the strip-till operation, granular urea fertilizer (46-0-0) was broadcast in conventionally tilled plots. After fertilizing, conventionally tilled plots were tilled using a 1.83-m wide rotary tiller (New Holland 105A; CNH America, LLC, New Holland, PA, USA) that tilled soil to a depth of 15-18 cm. To more accurately simulate commercial conventional tillage operations, we used a coulter to firm the seedbed after roto-tilling. During 2010, all plots were tilled on 20 April. During 2011, strip-till plots were tilled on 6 May, and conventionally tilled plots were tilled on 13 May. During 2012, strip-till plots were tilled on 18 April, and conventionally tilled plots were tilled on 20 April.

We used the glyphosate-resistant sugar beet variety 36RR11 (Betaseed, Inc., Shakopee, MN, USA), which is susceptible to the pathogens and insects observed in this study. The following fungicide seed treatments were used: tetramethylthiuram disulfide at a rate of 2.5 g active ingredient per kg seed and metalaxyl at a rate of 0.15 g active ingredient per kg seed. Seed was planted across the entire study area at a rate of 27,972 seeds per hectare with 56-cm row spacing using a four-row WIC vacuum planter (WIC, Inc., Halstad, MN, USA). Plots were planted on 30 April 2010, 14 May 2011, and 24 April 2012.

Treatments were assigned in a randomized split-plot design with blocks split by tillage (conventional or strip tillage) treatments, and irrigation treatment plots randomized within tillage treatment blocks. We used twelve-row plots (6.7 m wide) during 2010 and sixteen-row plots (8.9 m wide) during 2011 and 2012 with six tillage × irrigation treatment replicates each year. Each plot was 10.6 m long, with 3.05 m alleys (maintained as bare ground) between each block. Irrigation treatments featured four irrigation levels based on evapotranspiration (ET) rates of conventionally tilled sugar beet (125, 100, 75, and 50% of ET). ET was based on the Penman-Monteith model (Monteith and Unsworth, 2008) for conventionally tilled sugar beet. Weather data used for this model was collected from a weather station maintained by the US Bureau of Reclamation's AgriMet network (www.usbr.gov/pn/agrimet/), which was located no further than 0.9 km from the study site each year. Plots were watered independently from one another using a solid-set irrigation system. Each plot was irrigated using a single line of Nelson model 7081 15SQ spray heads (Nelson Irrigation Corporation, Walla Walla, WA, USA) mounted on vertical pipe risers 1.22 m above ground level and spaced 1.5 m apart (seven risers per plot) positioned between the two center rows of each plot. Immediately after planting, an equal amount of water was sprinkler-applied at three- to four-day intervals across the entire study site to aid with sugar beet emergence. Irrigation treatments were implemented after most seedlings had emerged.

Plots were harvested immediately following defoliation of beets using a two-row rubber flail topper on 11 Oct 2010, 12 Oct 2011, and 8 Oct 2012 using a two-row plot harvester. For yield data, we considered only two rows of each plot: rows 8 and 9 during 2010 and rows 12 and 13 during 2011-2012. These sets of rows received the most uniform irrigation. From the yield rows of each plot, we collected two samples of eight to ten beets and submitted them to The Amalgamated Sugar Company Beet Quality Lab (Paul, ID, USA) to determine percent sucrose and estimated recoverable sucrose (ERS). The mean of the two samples from each plot was used for data analysis. Percent sucrose was determined using an Autopol 880 polarimeter (Rudolph Research Analytical, Hackettstown, NJ, USA) and a half-normal weight sample dilution and aluminum sulfate clarification method [ICUMSA Method GS6-3 1994]. Conductivity was measured using a Foxboro conductivity meter Model 250 (Denver Instruments, Denver, CO, USA) with Orion probes 900200 and 9300 BNWP (Krackler Scientific, Inc., Albany, NY). ERS yield per hectare (ha) of roots was calculated using the following equation: [(extraction) × (0.01) × (gross sucrose/ha)]/(t/ha) , where extraction = 250 + [[(1255.2) × (conductivity) – (15,000) × (percent sucrose – 6,185)]/[(percent sucrose) × (98.66 – [(7.845) × (conductivity)])]] and gross sucrose = [[(t/ha) × (percent sucrose)] × (0.01)] × (1,000 kg/t) (Krackler Scientific. Inc., Albany, NY).

Weed sampling

Weed control was achieved by applying glyphosate to all plots three times during each growing season at a rate of 2.12 kg ae/ha. During 2010, glyphosate was applied on 31 May, 23 June, and 15 July. During 2011, glyphosate applications were made on 10 June, 14 June, and 1 July. During 2012, glyphosate applications were made on 21 May, 4 June, and 14 July. Weed responses to experimental treatments were assessed both within and between sugar beet rows in order to take into consideration the stratification of disturbed and undisturbed soil in strip-tilled plots. We recorded weed densities by species four times over each season by counting weed incidence within a fixed 0.125 m^2 area both within and between the designated harvest rows of each sub-plot.

We sampled five weed species over the course of the study: common lambsquarters (*Chenoopodium album* L.), green foxtail (*Setaria viridis* (L.) Beauv.), redroot pigweed (*Amaranthus retroflexus* L.), hairy nightshade (*Solanum sarrachoides* Sendtner), and annual sowthistle (*Sonchus oleraceus* L.). The former two species were most abundant in the study plots, which allowed for statistical analyses of these two species in addition to total weed counts.

Insect sampling

Plots were scouted for common insect pests of sugar beet in Idaho, including: beet leafminer (*Pegomya betae* Curtis), bean aphid (*Aphis fabae* Scopoli), sugar beet root aphid *(Pemphigus betae* Fitch), beet leafhopper (*Circulifer tenellus* (Baker)), sugar beet root maggot (*Tetanops myopaeformis* (Röder)), wireworms (including *Limonius californicus* (Mannerheim)), and cutworms (including *Euxoa auxiliaris* (Grote) and *Agrotis orthogonia* Morrison). Only beet leafminers and bean aphids were found in adequate enough numbers to justify sampling across plots and making statistical comparisons among treatments.

Beet leafminer densities were assessed in each plot by counting the total number of eggs and larvae per plant on five plants in each of the two harvest rows. Sampled plants were selected in a stratified random sampling scheme. Only unhatched eggs and live larvae were counted. Three counts were made over each of the three seasons; however, no larvae were observed during the first count in 2010 and eggs were observed only in extremely low abundance during the last count in 2010, so they were not counted. Bean aphid incidence was assessed by determining the presence or absence of aphids on each plant in the two harvest rows, with one assessment during 2010 and three during 2011. Aphid abundance during 2012 was too low to allow for statistical comparisons among treatments, and the data from this year are not presented.

Disease sampling

During stand establishment, sugar beet seedlings were observed for symptoms of “damping off,” which is associated with the soil-borne pathogens *Aphanomyces cochlioides*, *Rhizoctonia solani*, and *Pythium ultimum* (Harveson et al. 2009). Frequent stand counts in the yield data rows were used to observe the effects of soil-borne pathogens on plant population during the growing season and to calculate the area under disease progress curve (AUDPC, Jeger and Viljanen-Rollinson, 2001). In addition, each sugar beet root collected at harvest was visually inspected and rated for *A. cochlioides* and *R. solani* using established rating scales (1 = healthy to 9 = plant dead), and these ratings were used to calculate a Disease Index (DI) for each plot (Büttner et al., 2004). No efforts were undertaken to distinguish between *R. solani* AG 2-2 IIB and IV since only low disease incidence was observed. In addition, plots were scouted for foliar symptoms related to soil-borne and foliar pathogens, but no such symptoms were observed with high enough incidence to justify sampling across plots.

Data analysis

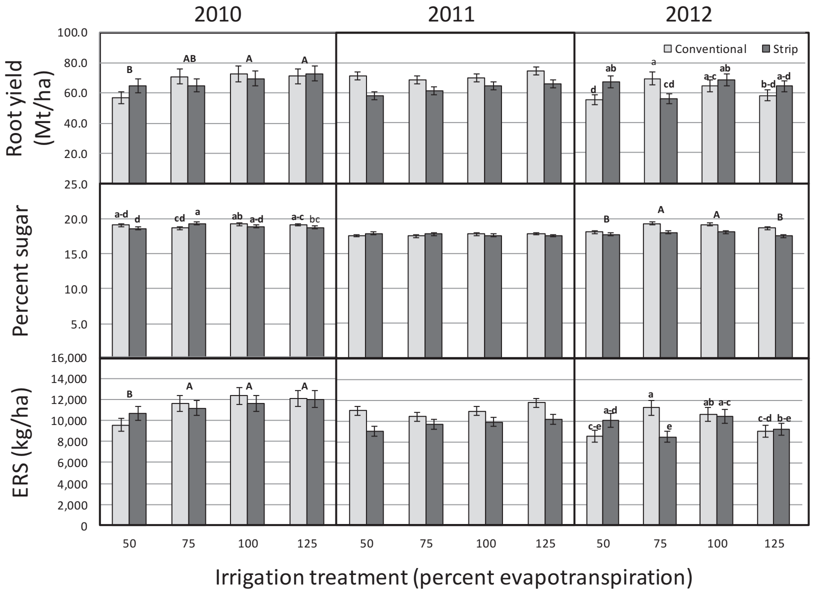
Data were analyzed using generalized linear mixed models (GLMM). Yield, weed counts, moisture content, and disease data were analyzed as split-plot designs with a factorial arrangement of two tillage and four ET treatments as fixed treatment effects and six blocks as random effects. Analysis of variance (ANOVA) models included interactions between tillage and irrigation treatments as well as block and tillage treatment interactions. We analyzed the following response variables: clean yield, percent sucrose, estimated recoverable sucrose, conductivity, and nitrate levels; total weed counts within and between rows, common lambsquarters within and between rows, and green foxtail within and between rows; soil moisture content; and area under the disease progress curve (AUDPC), disease index (DI), and disease incidence for infection with *R. solani* (Büttner et al., 2004, Jeger and Viljanen-Rollinson, 2001). Leafminer data were analyzed separately for each sampling date using split-split plot ANOVA with two tillage types and four ET treatments as the fixed effects, and the six blocks as the random effect. ANOVA models included all relevant interaction terms. Response variables for leafminer data were the number of eggs per plant and the number of larvae per plant on each sampling date. Bean aphid data were analyzed with the same model setup as was used for leafminers, except that date was included in the 2011 data as a fixed effect instead of performing separate analyses by date. The response variable for the bean aphid data was the proportion of plants infested (i.e., with any number of aphids) in each plot. Where ANOVA showed significant differences among treatments, we used least square means tests to discriminate among means. Analyses were conducted using PROC GLIMMIX in SAS 9.4 (SAS Institute 2017), with significance level set at = 0.05.

RESULTS

Yield

During 2010, no significant effects were observed for any yield parameters with respect to tillage treatment (Table 1). We observed significant effects of irrigation treatments on clean root yield and ERS (Table 1). Root yield was lower in 50% ET treatments relative to 100 and 125% treatments, but yield in 75% treatments did not differ from the other three treatments (Figure 1). ERS was lower in 50% treatments

Figure 1. Effects of tillage and irrigation treatments on clean root yield, percent sugar, and estimated recoverable sucrose (ERS) in sugar beet plots in 2010-2012. Error bars represent SE. Bars that share a letter are not significantly different based on least significant difference tests (α = 0.05); for cases in which the interaction term was not significant, letters discriminate only among the four irrigation treatments (with tillage treatment pooled).



relative to the other treatments, which did not differ among each other (Figure 1). We also observed a significant tillage by irrigation interaction effect on sugar content (Table 1); the pattern was not clearly defined, but pairwise comparisons showed higher percent sugar in the 100 and 125% ET conventional plots compared to the 50% strip-till plots (Figure 1).

During 2011, both clean root yield and ERS differed between tillage treatments (Table 1), with higher values for both parameters in conventionally tilled plots (root yield: 63,487 ± 975 Mt/ha for conventional versus 55,853 ± 975 Mt/ha for strip; ERS: 9,832 ± 186 kg/ha for conventional versus 8,647 ± 186 kg/ha for strip). Irrigation exhibited a significant effect only on nitrate levels, with the two lowest irrigation treatments (50 and 75% ET) exhibiting higher levels than the two higher ET treatments (Table 1; Table 2). No significant tillage by irrigation interaction effects were observed (Table 1).

During 2012, percent sugar, conductivity, and nitrates showed a significant response to tillage (Table 1), with conventional tillage having greater percent sugar (18.8 ± 0.12 versus 17.8 ± 0.12) and lower conductivity (0.676 ± 0.013 versus 0.713 ± 0.014) and nitrate (95.1 ± 12.6 versus 186.4 ± 22.5) levels. Both percent sugar and conductivity differed significantly among irrigation treatments (Table 1), with percent sugar being higher in 75 and 100% ET than the other treatments, which did not differ between each other (Figure 1), and conductivity being higher in 125% ET relative to the other three treatments, which did not differ among each other (Table 2). Both clean yield and ERS exhibited a significant tillage by irrigation interaction effect (Table 1); several significant differences were observed, but with no clearly discernable pattern (Figure 1).

Weeds

During 2010, counts of total weeds, common lambsquarters, and green foxtail did not differ by tillage treatment, irrigation treatment, or tillage by irrigation interactions for between-row nor for within-row counts (Table 3).

During 2011, total weed counts did not differ by tillage or irrigation treatment or their interaction either for within- or between-row counts (Table 3). Common lambsquarters densities between rows did not differ by tillage treatment, nor was the interaction term significant (Table 3). However, between-row counts of common lambsquarters differed among irrigation treatments (Table 3); 50% ET plots had fewer common lambsquarters than the other treatments, which did not differ among each other (Table 4). Within-row counts of common lambsquarters did not differ between tillage or among irrigation treatments, nor was the interaction term significant (Table 3). Green foxtail densities within rows were significantly higher in strip tillage (1.75 ± 0.29) relative to conventional tillage (0.67 ± 0.18), but densities between the rows were not affected by tillage treatment (Table 3). Green foxtail counts also were

Table 1. ANOVAs showing effects of tillage and irrigation treatments and their interaction on clean root yield, percent sugar, estimated recoverable sucrose (ERS), conductivity, and nitrate levels in sugar beet during 2010-2012.

Source of Variation	Numerator df	Denominator df	F	P
2010				
Root Yield				
Tillage	1	5	0.02	0.897
Irrigation	3	30	3.3	0.032
Tillage × Irrigation	3	30	1.2	0.329
Percent Sugar				
Tillage	1	5	0.93	0.380
Irrigation	3	30	0.68	0.569
Tillage × Irrigation	3	30	4.8	0.008
ERS				
Tillage	1	5	0.0	0.967
Irrigation	3	30	4.0	0.017
Tillage × Irrigation	3	30	0.85	0.476
Conductivity				
Tillage	1	5	0.76	0.424
Irrigation	3	30	2.5	0.079
Tillage × Irrigation	3	30	1.1	0.378
Nitrate				
Tillage	1	5	0.01	0.929
Irrigation	3	30	0.47	0.704
Tillage × Irrigation	3	30	2.1	0.122
2011				
Root Yield				
Tillage	1	5	65.1	0.001
Irrigation	3	30	2.0	0.142
Tillage × Irrigation	3	30	0.71	0.552
Sugar				
Tillage	1	5	0.05	0.839
Irrigation	3	30	0.10	0.959
Tillage × Irrigation	3	30	2.0	0.144

Source of Variation	Numerator df	Denominator df	F	P
ERS				
Tillage	1	5	118.1	<0.001
Irrigation	3	30	1.9	0.160
Tillage × Irrigation	3	30	0.73	0.545
Conductivity				
Tillage	1	5	0.07	0.798
Irrigation	3	30	0.04	0.987
Tillage × Irrigation	3	30	2.4	0.092
Nitrate				
Tillage	1	5	1.57	0.266
Irrigation	3	30	4.5	0.001
Tillage × Irrigation	3	30	1.08	0.373
2012				
Root Yield				
Tillage	1	5	0.52	0.505
Irrigation	3	30	1.2	0.327
Tillage × Irrigation	3	30	6.1	0.002
Percent Sugar				
Tillage	1	5	30.3	0.003
Irrigation	3	30	6.2	0.002
Tillage × Irrigation	3	30	2.0	0.140
ERS				
Tillage	1	5	0.36	0.574
Irrigation	3	30	2.8	0.060
Tillage × Irrigation	3	30	5.6	0.004
Conductivity				
Tillage	1	5	10.0	0.025
Irrigation	3	30	5.9	0.003
Tillage × Irrigation	3	30	1.7	0.200
Nitrate				
Tillage	1	5	31.0	0.003
Irrigation	3	30	1.5	0.237
Tillage × Irrigation	3	30	1.2	0.339

Table 2. Comparisons of conductivity and nitrate among irrigation treatments (% ET) in harvested sugar beet during 2010-2012. Means within a column that share a letter are not significantly different based on least square means tests (α = 0.05) (n = 12).

	2010			2011			2012		
Conductivity									
50% ET	0.690	±	0.018	0.823	±	0.029	0.699	±	0.020a
75% ET	0.729	±	0.018	0.825	±	0.029	0.650	±	0.018a
100% ET	0.751	±	0.018	0.824	±	0.029	0.678	±	0.019a
125% ET	0.743	±	0.018	0.811	±	0.029	0.754	±	0.021b
Nitrate									
50% ET	27.7	±	3.90	288.2	±	23.4b	119.6	±	21.2
75% ET	36.7	±	7.26	287.5	±	23.4b	111.9	±	25.1
100% ET	29.5	±	5.99	200.8	±	13.9a	139.5	±	26.6
125% ET	33.5	±	5.27	227.1	±	18.7a	191.9	±	37.3

not affected by irrigation treatment or tillage by irrigation interaction (Table 3).

During 2012, total weed counts between rows did not differ between tillage treatments or among tillage by irrigation interactions (Table 3). However, total weed counts between rows differed among irrigation treatments (Table 3), with 125% ET having higher total counts than either the 50% or the 75% treatments and 100% ET plots being intermediate (Table 4). Within-row counts of total weeds showed no response to tillage or irrigation treatment, and the interaction effect also was not significant (Table 3). Both common lambsquarters and green foxtail showed no response to tillage treatment, irrigation treatment, or tillage by irrigation interaction (Table 3).

Beet leafminers

On both dates in 2010 when egg data were collected, densities of beet leafminer eggs were higher in conventionally tilled plots than strip-till plots (Table 5; Table 6). Egg density did not differ by tillage treatment during 2011 (Table 5). In 2012, egg density did not differ by tillage treatment for the first two sample dates, but for the third date was significantly higher in conventionally tilled plots relative to strip-till plots (Table 5; Table 6). Leafminer larvae showed no response to tillage treatment at any time during the study (Table 5).

Leafminer egg densities differed by irrigation treatment only during the first sample date of 2012 (Table 5). Fewer eggs were observed in the

Table 3. ANOVAs comparing weed counts between tillage and among irrigation treatments both between and within sugar beet rows during 2010-2012.

	Between rows				Within rows			
Source of Variation	Numerator df	Denominator df	F	P	Numerator df	Denominator df	F	P
2010								
Total weeds								
Tillage	1	5	0.52	0.504	1	5	2.6	0.169
Irrigation	3	30	1.7	0.184	3	30	0.65	0.590
Tillage × Irrigation	3	30	2.9	0.053	3	30	2.2	0.112
Common lambsquarters								
Tillage	1	5	6.0	0.058	1	5	0.36	0.574
Irrigation	3	30	2.4	0.092	3	30	0.14	0.938
Tillage × Irrigation	3	30	1.1	0.374	3	30	0.05	0.983
Green foxtail								
Tillage	1	5	0.74	0.429	1	5	0.23	0.654
Irrigation	3	30	1.0	0.392	3	30	0.20	0.897
Tillage × Irrigation	3	30	1.3	0.282	3	30	0.47	0.706
2011								
Total weeds								
Tillage	1	5	1.7	0.249	1	5	0.02	0.900
Irrigation	3	30	0.08	0.971	3	30	0.45	0.717
Tillage × Irrigation	3	30	0.20	0.893	3	30	0.96	0.424

Table 3 continued

	Between rows				Within rows			
Source of Variation	Numerator df	Denominator df	F	P	Numerator df	Denominator df	F	P
Common lambsquarters								
Tillage	1	5	4.2	0.096	1	5	0.36	0.575
Irrigation	3	30	5.2	0.005	3	30	0.72	0.545
Tillage × Irrigation	3	30	2.5	0.078	3	30	0.64	0.594
Green foxtail								
Tillage	1	5	0.20	0.677	1	5	10.2	0.024
Irrigation	3	30	0.14	0.935	3	30	0.68	0.574
Tillage × Irrigation	3	30	0.01	0.998	3	30	0.23	0.874
2012								
Total weeds								
Tillage	1	5	0.34	0.585	1	5	0.94	0.378
Irrigation	3	30	4.2	0.013	3	30	1.1	0.381
Tillage × Irrigation	3	30	0.13	0.943	3	30	0.24	0.870
Common lambsquarters								
Tillage	1	5	0.10	0.766	1	5	0.01	0.924
Irrigation	3	30	0.03	0.993	3	30	1.1	0.375
Tillage × Irrigation	3	30	0.03	0.992	3	30	1.4	0.271
Green foxtail								
Tillage	1	5	0.33	0.591	1	5	2.3	0.193
Irrigation	3	30	0.13	0.944	3	30	0.81	0.497
Tillage × Irrigation	3	30	0.08	0.972	3	30	0.63	0.604

Table 4. Mean ± SE weed counts in response to different irrigation treatments in 2010-2012. For each weed group, means within a column that share a letter are not significantly different based on least square means tests ($\alpha = 0.05$) (n = 12).

	Between rows									Within rows								
Total weeds	2010			2011			2012			2010			2011			2012		
50% ET	6.42	±	1.53	16.50	±	10.75	8.08	±	1.53a	9.50	±	2.59	11.58	±	3.18	16.58	±	4.56
75% ET	9.42	±	4.26	13.92	±	2.16	7.58	±	1.19a	8.42	±	2.76	9.25	±	2.10	11.17	±	2.17
100% ET	9.25	±	1.51	11.08	±	2.44	12.92	±	2.91ab	11.75	±	3.03	10.00	±	1.59	20.00	±	4.33
125% ET	16.08	±	4.95	11.67	±	2.38	19.25	±	5.17b	13.00	±	3.28	8.58	±	1.59	19.00	±	5.42
Common lambsquarters																		
50% ET	2.08	±	0.65	1.75	±	0.81a	3.33	±	0.90	3.67	±	1.43	5.17	±	2.36	9.42	±	3.57
75% ET	0.75	±	0.30	7.25	±	1.41b	2.83	±	0.47	1.75	±	0.54	4.83	±	1.38	4.25	±	1.19
100% ET	1.08	±	0.50	4.58	±	1.26b	3.67	±	0.88	1.33	±	0.59	5.00	±	1.62	8.83	±	2.51
125% ET	1.08	±	0.31	3.92	±	1.02b	6.42	±	2.98	3.00	±	0.80	2.75	±	0.98	8.25	±	3.00
Green foxtail																		
50% ET	3.00	±	0.92	1.33	±	0.86	3.58	±	0.90	3.75	±	1.47	1.08	±	0.36	5.50	±	1.48
75% ET	7.58	±	4.14	2.92	±	1.22	4.08	±	0.90	5.08	±	2.60	1.25	±	0.35	5.58	±	1.80
100% ET	6.75	±	1.58	1.08	±	0.63	8.42	±	2.53	7.67	±	2.72	0.92	±	0.36	9.50	±	3.77
125% ET	13.42	±	4.90	3.25	±	1.07	10.25	±	4.47	7.33	±	3.06	1.58	±	0.43	8.42	±	2.45

Table 5. ANOVAs for the effects of tillage and irrigation treatments on the number of beet leafminer eggs or larvae per sugar beet plant across sample dates during 2010-2012.

	2010			2011			2012		
	7 June[a]	21 June	7 July[b]	15 June	29 June	13 July	1 June	11 June	21 June
Eggs per plant									
Tillage									
$F_{1,5}$	23.50	21.21	—	0.35	2.38	0.28	0.62	0.74	19.22
P-value	0.005	0.006	—	0.582	0.184	0.619	0.467	0.430	0.007
Irrigation									
$F_{3,15}$	0.50	0.87	—	0.36	1.01	0.09	6.92	1.23	1.37
P-value	0.688	0.480	—	0.785	0.415	0.967	0.004	0.333	0.290
Tillage × Irrigation									
$F_{3,15}$	0.84	0.10	—	3.12	1.23	0.89	2.30	0.58	0.65
P-value	0.495	0.962	—	0.058	0.335	0.467	0.119	0.636	0.596
Larvae Per Plant									
Tillage									
$F_{1,5}$	—	0.93	0.29	0.73	1.95	5.20	1.73	0.11	1.13
P-value	—	0.380	0.612	0.433	0.222	0.072	0.245	0.756	0.337
Irrigation									
$F_{3,15}$	—	3.77	2.26	1.50	1.77	1.56	1.05	0.26	1.12
P-value	—	0.034	0.123	0.256	0.196	0.242	0.399	0.856	0.373
Tillage × Irrigation									
$F_{3,15}$	—	0.40	0.19	0.49c	0.26	0.44c	0.57	0.10	0.60
P-value	—	0.752	0.904	0.696	0.853	0.728	0.641	0.956	0.627

[a] Larvae were not observed on this date.

[b] Eggs were observed in extremely low abundance and thus were not counted on this date.

[c] Denominator df = 14.

Table 6. Mean ± SE values of leafminer eggs and larvae per sugar beet plant for the different tillage and irrigation treatments across sampling dates in 2010-2012. Means for each main effect within a column that share a letter are not significantly different based on least square means tests ($\alpha = 0.05$).

	2010			2011			2012		
	7 June[a]	21 June	7 July[b]	15 June	29 June	13 July	1 June	11 June	21 June
Eggs per plant									
Tillage									
Conventional	1.87 ± 0.13b	36.88 ± 2.20b	—	4.70 ± 0.33	7.30 ± 0.53	9.72 ± 0.92	9.89 ± 1.23	10.10 ± 1.25	20.32 ± 1.87b
Strip	0.96 ± 0.11a	26.79 ± 1.56a	—	4.38 ± 0.27	6.70 ± 0.49	11.72 ± 1.67	8.23 ± 0.79	7.90 ± 0.62	13.82 ± 1.37a
Irrigation									
50% ET	1.37 ± 0.17	30.96 ± 2.19	—	4.87 ± 0.49	7.03 ± 0.63	10.10 ± 1.56	10.58 ± 1.69b	8.81 ± 1.83	18.08 ± 3.07
75% ET	1.30 ± 0.24	30.81 ± 2.99	—	4.20 ± 0.38	7.45 ± 0.68	9.97 ± 1.33	10.66 ± 1.38b	9.60 ± 1.10	18.08 ± 1.93
100% ET	1.40 ± 0.23	36.03 ± 4.02	—	4.46 ± 0.41	7.19 ± 0.80	10.91 ± 1.88	9.07 ± 1.57b	9.57 ± 1.68	18.34 ± 2.98
125% ET	1.60 ± 0.24	29.54 ± 2.73	—	4.64 ± 0.43	6.33 ± 0.81	11.91 ± 2.76	5.93 ± 0.81a	8.03 ± 1.01	13.76 ± 1.72
Larvae Per Plant									
Tillage									
Conventional	—	3.20 ± 0.29	9.03 ± 0.48	0.85 ± 0.11	2.36 ± 0.35	4.93 ± 1.14	1.45 ± 0.10	1.15 ± 0.16	1.50 ± 0.24
Strip	—	2.93 ± 0.24	8.57 ± 0.38	0.61 ± 0.07	2.76 ± 0.36	3.49 ± 1.02	1.36 ± 0.15	1.04 ± 0.13	1.14 ± 0.22
Irrigation									
50% ET	—	2.82 ± 0.45a	7.61 ± 0.33	0.82 ± 0.13	2.08 ± 0.46	3.46 ± 1.14	1.13 ± 0.12	1.23 ± 0.25	1.59 ± 0.45
75% ET	—	2.60 ± 0.31a	8.79 ± 0.85	0.62 ± 0.12	2.38 ± 0.49	3.73 ± 1.35	1.51 ± 0.12	1.18 ± 0.21	1.30 ± 0.24
100% ET	—	3.28 ± 0.41ab	9.60 ± 0.50	0.69 ± 0.14	2.63 ± 0.52	4.26 ± 1.51	1.56 ± 0.16	0.89 ± 0.08	1.60 ± 0.41
125% ET	—	3.56 ± 0.28b	9.18 ± 0.55	0.80 ± 0.13	3.14 ± 0.52	5.39 ± 2.10	1.43 ± 0.27	1.08 ± 0.23	0.80 ± 0.10

[a] Larvae were not observed on this date.

[b] Eggs were observed in extremely low abundance and thus were not counted on this date.

125% ET treatment relative to all other treatments, which did not differ among each other (Table 6). There were no significant differences among irrigation treatments with regard to egg densities on any other sample date (Table 5). The number of larvae per plant sampled differed among irrigation treatments only during the second sample date of 2010 (Table 5). We observed significantly more larvae in 125% ET than in 50 and 75% ET treatments, but the number of larvae per plant in the 50, 75, and 100% ET plots did not differ from each other (Table 6). There were no significant differences among irrigation treatments with regard to larval densities on any other sample date (Table 5). There were no significant interaction effects between tillage and irrigation treatments for either eggs or larvae at any time during this study (Table 5).

Bean aphids

The proportion of plants infested with bean aphids did not differ between tillage treatments during 2010 (conventional: 0.429 ± 0.062; strip till: 0.373 ± 0.056; $F_{1,5} = 0.19$, $P = 0.683$). There was a significant irrigation effect in 2010 ($F_{3,15} = 13.31$, $P < 0.001$), with the 50% ET treatment (0.160 ± 0.044) having a lower density than all others, and the 75% ET treatment (0.361 ± 0.062) being significantly lower than the 100% (0.536 ± 0.081) and 125% treatments (0.547 ± 0.089), which did not differ from each other. There was no significant interaction between tillage and irrigation ($F_{3,15} = 0.19$, $P = 0.901$).

During 2011 the proportion of plants with bean aphids did not differ between conventional (0.086 ± 0.012) and strip till (0.088 ± 0.013) (Table 7). There was not a significant irrigation effect (Table 7); however, bean aphid incidence was numerically higher with increased irrigation rate (50% ET: 0.056 ± 0.013, 75% ET: 0.079 ± 0.016, 100% ET: 0.093 ± 0.018, 125% ET: 0.120 ± 0.022). The proportion of plants infested differed significantly among sampling dates. On 11 August the infestation proportion (0.045 ± 0.009) was significantly lower than on 2 August (0.119 ± 0.017) and 26 August (0.098 ± 0.017), which did not differ from each other (Table 7). The 2011 model contained no significant interaction terms (Table 7).

Table 7. ANOVA for the proportion of sugar beet plants infested with bean aphids in 2011 tillage and irrigation treatments at three different dates.

Source of Variation	Numerator df	Denominator df	F	P
Tillage	1	5	0.01	0.942
Irrigation	3	30	2.15	0.114
Date	2	80	7.26	0.001
Tillage × Irrigation	3	30	0.82	0.491
Date × Tillage	2	80	0.41	0.662
Date × Irrigation	6	80	0.81	0.562
Date × Tillage × Irrigation	6	80	0.34	0.912

Plant pathogens

Over all three years of the study, no symptoms of seedlings "damping off' associated with the soil-borne pathogens *A. cochlioides*, *R. solani*, or *P. ultimum* were observed. Moreover, symptoms caused by *A. cochlioides* were not observed on harvested roots. Only symptoms of root rot caused by *R. solani* were observed and rated during harvest. During 2011, AUDPC differed significantly by tillage treatment, with conventional tillage having a higher AUDPC (Table 8). AUDPC did not differ by irrigation treatment (Table 9). Incidence and DI did not differ by tillage (Table 8) or irrigation treatment (Table 9). There were no significant interaction effects between tillage and irrigation for AUDPC ($F_{3,30}$ = 0.22, P = 0.883), DI ($F_{3,30}$ = 0.69, P = 0.563), or incidence ($F_{3,30}$ = 0.46, P =0.715). During 2012, there were no significant effects for AUDPC, DI, or incidence by tillage (Table 8) or irrigation treatments (Table 9). There were no significant interaction effects between tillage and irrigation for any of the three response variables ($F_{3,30}$ = 0.71, P = 0.556; $F_{3,30}$ = 1.32, P = 0.287; or $F_{3,29}$ = 2.36, P = 0.92, respectively).

Table 8. Effects of tillage treatment on Rhizoctonia ratings (area under the disease progress curve [AUDPC], disease index [DI], and disease incidence) on sugar beet in 2011-2012.

	2011			2012		
	AUDPC	DI	Incidence	AUDPC	DI	Incidence
Conventional	26.34 ± 1.20	75.31 ± 2.44	82.18 ± 2.70	66.35 ± 3.48	25.57 ± 1.48	23.60 ± 2.03
Strip	23.30 ± 1.05	70.85 ± 3.52	76.90 ± 4.22	64.45 ± 3.55	28.60 ± 1.86	21.05 ± 2.03
$F_{1,5}$	17.89	0.80	0.97	0.21	1.15	0.10
P-value	0.008	0.413	0.370	0.665	0.333	0.767

Table 9. Effects of irrigation treatment on Rhizoctonia ratings (area under the disease progress curve [AUDPC], disease index [DI], and incidence) on sugar beet in 2011-2012 (n = 12).

	2011			2012		
	AUDPC	DI	Incidence	AUDPC	DI	Incidence
50% ET	25.97 ± 1.89	73.13 ± 2.85	80.86 ± 3.40	64.85 ± 4.70	26.37 ± 2.33	22.07 ± 1.67
75% ET	23.71 ± 1.47	76.16 ± 3.23	82.57 ± 3.34	61.44 ± 6.63	27.49 ± 2.66	26.62 ± 4.22
100% ET	25.78 ± 1.91	71.61 ± 5.89	77.19 ± 7.11	68.39 ± 3.74	27.27 ± 1.71	21.63 ± 2.19
125% ET	23.83 ± 1.27	71.41 ± 4.91	77.54 ± 5.68	66.92 ± 4.62	27.22 ± 2.98	18.98 ± 2.60
$F_{3,30}$	0.46	0.20	0.26	0.49	0.09	0.49a
P-value	0.709	0.899	0.853	0.692	0.963	0.689

DISCUSSION

Numerous studies have shown conservation tillage practices in sugar beet to produce yields that are comparable to conventional tillage (Halvorson and Hartman, 1984; Miyazawa et al., 2004; Overstreet, 2009; Evans et al., 2010; Stevens et al., 2010; Tarkalson et al., 2012). The results presented here are mostly consistent with this pattern. Over the course of the three-year study, we generally observed similar yields between tillage treatments, with no consistent effects of tillage on any of the five yield parameters. Only during 2011 were clean yield and ERS lower for strip-tilled versus conventionally tilled treatments. Yield differences between tillage treatments during 2011 might be explained in part by variation in precipitation among years. Cumulative precipitation was similar among years during the two weeks following planting (1.75, 1.85, and 1.27 cm, respectively). However, during this period of stand establishment, rainfall occurred almost daily during 2011 whereas it occurred sporadically during 2010 and on only one day during 2012. Persistently wet soil with lower near-soil surface temperatures due to evaporative cooling may have contributed to delayed germination and/or plant development in strip-tillage plots. Conservation tillage contributes to higher soil moisture (Sojka et al., 1980; Deibert, 1983) and a cooler, moister seedbed environment compared to conventional tillage (Hatfield et al., 2001; Overstreet, 2009), and Evans et al. (2010) reported that emergence of sugar beet seedlings in strip-tilled fields was delayed in years with higher precipitation rates.

For the few cases in which yield effects from irrigation treatments were observed, generally responses were consistent with water stress being an important cause of yield loss in sugar beet (Rytter, 2005; Bloch et al., 2006; Hoffmann, 2010). However, only the lowest irrigation rate exhibited notable yield reductions, and only during one year (2010), suggesting that sugar beet in our study was resilient to less severe deviations from an optimal irrigation rate. Similarly, percent sugar content was only somewhat affected by irrigation rate in the present study. Higher sugar content has been observed under deficit irrigation (Mahmoodi et al., 2008; Abyaneh et al., 2017; Malik et al., 2018), though responses may vary from year to year, potentially due to differences in the timing of water stress (Tarkalson and King, 2017). In any event, strip-till sugar beet production in Idaho appears to be compatible with the standard irrigation practices used for conventional tillage.

Conductivity and nitrate content were largely unaffected by tillage treatments, differing only during 2012. Higher conductivity under strip tillage likely was directly related to the higher nitrates observed in roots from strip-tilled plots during this year. Higher nitrate levels in roots could result from higher soil nitrate levels associated with crop residue in conservation tillage (Zhang et al. 2016). Interestingly, 2012 was the only year in which percent sugar responded to tillage treatment. Sugar content is known to be inversely related to nitrate levels (Halvorson et al., 1978; Khan and McVay, 2014), so it is not surprising that percent sugar was lower in strip-tilled plots during this year. It is not clear why no such differences were observed during 2010-2011; however, year-to-year variation in tillage effects on nitrates also was reported by Sainju et al. (2013).

Water stress may contribute to a buildup of solutes, including nitrates, which reduce beet quality (Bloch et al., 2006). However, nitrates and conductivity showed limited responses to irrigation treatments used in the present study. The exceptions were during 2011 when nitrates were lower with higher irrigation rates and during 2012 when conductivity was higher with the highest irrigation treatment. The former pattern may be explained by higher irrigation rates moving fertilizer deeper into the soil profile and out of reach of plants (Barzegari et al., 2017). The reason for the latter pattern is unclear.

The weeds examined in this study were not greatly affected by tillage treatments. Each year of the study was the first year in which a portion of the soil was left undisturbed in that field. Changes in weed composition and emergence usually do not happen within the first 2 to 3 years of not disturbing the soil (Wrucke and Arnold 1985). The only significant tillage effect observed was for higher green foxtail counts within rows under strip tillage during 2011. In contrast, several studies across a variety of systems reported a reduction in weeds under strip tillage; however, these studies vary in location, weed species examined, and weed sampling methodology (Hendrix et al., 2004; Rapp et al., 2004; Wang and Ngouajio, 2008; Trevini et al., 2013; Gegner-Kazmierczak and Hatterman-Valenti, 2016). In general, weed management has long been considered a challenge under conservation tillage practices, including strip tillage (Morse, 1999; Morris et al., 2010). Furthermore, weed dynamics are complicated under strip tillage due to the interactions between the tilled and untilled zones (Brainard et al., 2013), so understanding patterns can be difficult. Nevertheless, the general lack of significant differences in weed counts between strip-tilled and conventionally tilled plots in this study shows that weed management may not be more difficult in strip-till production in our system.

The irrigation treatments used in this study also did not have major effects on weed densities. The only significant patterns observed were for between-row counts that were lower for common lambsquarters under 50% ET in 2011, and higher for total weeds under 125% ET in 2012. Both of these patterns may reflect a positive correlation between water availability and plant growth. Growth of common lambsquarters has been shown to be reduced by drought conditions (Maganti et al., 2005). While the patterns observed in our study provide limited evidence for water usage affecting weeds in a sugar beet crop, our results overall suggest that irrigation does not strongly affect weed densities in our system.

Although soil and litter-dwelling arthropod pests, including wireworms and cutworms, are expected to be favored by reduced tillage (All and Gallaher, 1976; Stinner and House, 1990; Tonhasca and Stinner, 1991), these groups were largely absent from our study. Only beet leafminers and bean aphids were abundant enough during this study to allow for comparisons among treatments. Higher oviposition rates of leafminers in conventionally tilled plots might be attributed to differences between tillage treatments with regard to microclimate, soil structure, or their effects on crop physiology (Phillips et al., 1980; Stinner and House, 1990; Sunderland et al., 1996). Female beet leafminer flies lay more eggs on larger leaves (EJW, personal observation), and sugar beet leaf growth is temperature dependent (Milford and Riley, 1980). The few differences in leafminer densities that we observed among irrigation treatments might also be related to treatment effects on sugar beet physiology that may have influenced visual or olfactory cues used by females to orient to host plants (Röttger and Klingauf, 1976; Röttger, 1979). Notably, any differences among treatments with respect to leafminer eggs was not reflected by similar differences in larval densities. This could possibly be a result of egg predation (Brust et al., 1986) or parasitism by natural enemies or by intraspecific competition among leafminer larvae; however, more work would be needed to clarify these possible explanations.

The bare soil of conventional tillage provides a more distinct color contrast with sugar beet foliage than does residue-covered soil (Heimbach and Garbe, 1996; Döring et al., 2004). Although such color contrast may play an important role in settling behavior of several species of aphids (Powell et al., 2006), we observed no such effect in the current study. It is possible that crop row closure made such visual cues less evident to alate bean aphids during infestation onset in late July. Bean aphid densities did show a positive relationship with irrigation rate, which could have been in response to host quality (Price, 1991; Powell et al., 2006; Rousselin et al., 2016). Any differences among treatments with respect to insect densities did not appear to be related to responses of natural enemies in this study (Daku, 2012).

Soil-borne and foliar plant pathogens did not play a major role in this study, as the only notable symptoms observed at harvest were due to *Rhizoctonia solani* causing Rhizoctonia root and crown rot on harvested beet roots. The overall low incidence and severity of *R. solani* at the research site is most likely related to long crop rotations and a lack of alternative hosts (Ruppel, 1985; Rush and Winter, 1990; Martin, 2003; Buhre et al., 2009). Contrary to previous studies (Bolton et al. 2010; Harveson and Rush, 2002; Rotem and Palti, 1969), irrigation had no effect on *R. solani* in this study, whereas tillage had only a minor effect. The AUDPC for soil-borne pathogens was higher in conventional tillage compared to strip tillage in 2011, but this pattern was not observed in 2012. Generally, tillage is considered an important practice for the reduction of both soil-borne and foliar fungal pathogens (Sumner et al., 1981, 1986); tillage breaks up mycelial networks and exposes crop residue to microbial decomposition (Paulitz et al., 2002). On the other hand, conventional tillage may favor disease severity and incidence due to poorer soil tilth, greater compaction, and higher soil moisture related to compaction (Bockus and Shroyer, 1998; Harris et al., 2003; Jabro et al., 2015; Kravchenko et al., 2011). The equivocal results in the present study may reflect these contrasting principles. The distribution and severity of *R. solani* observed here are consistent with other findings in sugar beet in this region, in which little difference between conventional and strip tillage was found (Strausbaugh and Eujayl, 2012). The results suggest that in our system *R. solani* incidence is no more severe under strip tillage compared to conventional tillage; however, more work is needed to fully understand the effects of tillage, irrigation, and crop rotation on other plant pathogens in sugar beet.

Differences in yield responses among the three years underscore how climatic variation among years can influence the relative agronomic value of strip versus conventional tillage. Yield responses to irrigation treatments suggest that current evapotranspiration models for conventional sugar beet are compatible with strip-till production. Densities of pests (including insects, weeds, and a plant pathogen) in this study generally were no higher and in some cases were lower for strip tillage than for conventional, indicating that pest management programs in this system should not be compromised by strip tillage. Future studies that feature heavier pressure from other key pests are needed in order to draw broader conclusions regarding pest responses to conservation tillage in sugar beet. However, the results presented here show that strip-till sugar beet can be produced with yields comparable to conventional tillage without strongly affecting the pest complex.

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LITERATURE CITED

Aase, J.K., and J.L. Pikul, Jr. 1995. Crop and soil response to long-term tillage practices in the northern Great Plains. Agron. J. 87: 652-656.

Abyaneh, H.Z., M. Jovzi, and M. Albaji. Effect of regulated deficit irrigation, partial root drying, and N-fertilizer levels on sugar beet crop (*Beta vulgaris* L.). Agr. Water Manage. 14: 13-23.

All, J.N., and R.N. Gallaher. 1976. Insect infestations in no-tillage corn cropping systems. Ga. Agric. Res. 17: 17-19.

Alletto, L., Y. Coquet, P. Benoit, D. Heddadj, and E. Barriuso. 2010. Tillage management effects on pesticide fate in soils: a review. Agron. Sustain. Dev. 30: 367-400.

Alletto, L., P. Benoit, E. Justes, and Y. Coquet. 2012. Tillage and fallow period management effects on the fate of the herbicide isoxaflutole in an irrigated continuous-maize field. Agric. Ecosyst. Environ. 153: 40-49.

The Amalgamated Sugar Company. 2015 Sugarbeet grower's guide book. The Amalgamated Sugar Company, LLC. Boise, ID.

Barzegari, M., A.R. Sepaskhah, and S.H. Ahmadi. 2017. Irrigation and nitrogen managements affect nitrogen leaching and root yield of sugar beet. Nutr. Cycl. Agroecosys. 108: 211-230.

Bloch, D., C.M. Hoffmann, and B. Marlander. 2006. Solute accumulation as a cause for quality losses in sugar beet submitted to continuous and temporary drought stress. J. Agron. Crop Sci. 192: 17-24.

Bockus, W.W., and J.P. Shroyer. 1998. The impact of reduced tillage on soilborne plant pathogens. Annu. Rev. Phytopathol. 36: 485-500.

Bolton, M. D., L. Panella, L. Campbell, and M.F.R. Khan. 2010. Temperature, moisture, and fungicide effects in managing Rhizoctonia root and crown rot of sugar beet. Phytopathology 100: 689-697.

Brainard, D.C., R.E. Peachey, E.R. Haramoto, J.M. Luna, and A. Rangarajan. 2013. Weed ecology and nonchemical management under strip-tillage: implications for northern US vegetable cropping systems. Weed Technol. 27: 218-230.

Bressan, A. 2009. Agronomic practices as potential sustainable options for the management of *Pentastiridius leporinus* (Hemiptera: Cixiidae) in sugar beet crops. J. Appl. Entomol. 133: 760-766.

Brust, G.E., B.R. Stinner, and D.A. McCartney. 1985. Tillage and soil insecticide effects on predator-black cutworm (Lepidotera: Noctuidae) interactions in corn agroecosystems. J. Econ. Entomol. 78: 1389-1392.

Brust, G.E., B.R. Stinner, and D.A. McCartney. 1986. Predation by soil inhabiting arthropods in intercropped and monoculture agroecosystems. Agric. Ecosyst. Environ. 18: 145-154.

Buhre, C., C. Kluth, K. Burcky, B. Marlander, and C. Varrelmann. 2009. Integrated control of root and crown rot in sugar beet: combined effects of cultivar, crop rotation, and soil tillage. Plant Dis. 93: 155-161.

Büttner, G., B. Pfähler, and B. Märländer. 2004. Greenhouse and field techniques for testing sugar beet for resistance to Rhizoctonia root and crown rot. Plant Breeding 123: 158-166.

Chauhan, B.S., G.S. Gill, and C. Preston. 2006. Tillage system effects on weed ecology, herbicide activity and persistence: a review. Aust. J. Exp. Agr. 46: 1557-1570.

Clark, M.S., J.M. Luna, N.D. Stone, and R.R. Youngman. 1994. Generalist predator consumption of armyworm (Lepidoptera: Noctuidae) and effect of predator removal on damage in no-till corn. Environ. Entomol. 23: 617-622.

Daku, K. 2012. Effects of tillage and irrigation practices on sugar beet insect pests and their natural enemies. M.S. Thesis, University of Idaho, 123 pp.

Deibert, E. J. 1983. The role of soil physical properties in managing reduced tillage systems. N. Dak. Farm Res. 41: 30-33.

Döring, T.F., S.M. Kirchner, S. Kühne, and H. Saucke. 2004. Response of alate aphids to green targets on coloured backgrounds. Entomol. Exp. Appl. 11: 53-61.

Evans, R.G., B.W. Stevens, and W.M. Iverson. (2010). Development of strip-tillage on sprinkler irrigated sugar beet. Appl. Eng. in Agric. 26: 59-69.

Gegner-Kazmierczak, S., and H. Hatterman-Valenti. 2016. Strip tillage and early-season broadleaf weed control in seeded onion (*Allium cepa*). Agriculture-Basel 6: Article Number 11 (doi:10.3390/agriculture 6020011).

Gencsoylu, I., and I. Yalcin. 2004. Advantages of different tillage systems and their effects on the economically important pests, *Thrips tabaci* Lind. and *Aphis gossypii* Glov. in cotton fields. J. Agron. Crop. Sci. 190: 381-388.

Hatfield, J.L., T.J. Sauer, and J.H. Prueger. 2001. Managing soils to achieve greater water use efficiency: A review. Agron. J. 93: 271-280.

Hajebi, A., T.K. Das, A. Arora, S.B. Singh, and F. Hajebi. 2016. Herbicide tank-mixes effects on weeds and productivity and profitability of chili (*Capsicum annum* L.) under conventional and zero tillage. Sci. Hortic-Amsterdam 198: 191-196.

Halvorson, A.D., and G.P. Hartman. 1984. Reduced seedbed tillage effects on irrigated sugarbeet yield and quality. Agron. J. 76: 603-606.

Halvorson, A.D., G.P. Hartman, D.F. Cole, V.A. Haby, and D.E. Baldridge. 1978. Effect of N fertilization on sugarbeet crown tissue production and processing quality. Agron. J. 70: 876-880.

Hammond, R.B., and B.R. Stinner. 1987. Soybean foliage insects in conservation tillage systems: effects of tillage, previous cropping history, and soil insecticide application. Environ. Entomol. 16: 524-531.

Harris, K., I.M. Young, C.A. Gilligan, W. Otten, and K. Ritz. 2003. Effect of bulk density on the spatial organisation of the fungus *Rhizoctonia solani* in soil. FEMS Microbiol. Ecol. 44: 45-56.

Harveson R. M., L. E. Hanson, and G. L. Hein. 2009. Compendium of Beet Diseases and Pests. APS Press, St. Paul, MN, USA.

Harveson, R. M., and C.M. Rush. 2002. The influence of irrigation frequency and cultivar blends on the severity of multiple root diseases in sugar beets. Plant Dis. 86: 901-908.

Heimbach, U., and V. Garbe. 1996. Effects of reduced tillage systems in sugar beet on predatory and pest arthropods. Act. Jutland. 71: 195-208.

Hendrix, B.J., B.G. Young, and S.K. Chong. 2004. Weed management in strip tillage corn. Agron. J. 96: 229-235.

Hoffmann, C.M. 2010. Sucrose accumulation in sugar beet under drought stress. J. Agron. Crop Sci. 196: 243-252.

Jabro, J.D., W.B. Stevens, W.M. Iversen, and R.G. Evans. 2011. Bulk density, water content, and hydraulic properties of a sandy loam soil following conventional or strip tillage. Appl. Eng. Agric. 27: 765-768.

Jeger, M.J., and S.L.H. Viljanen-Rollinson. 2001. The use of the area under the disease-progress curve (AUDPC) to assess quantitative disease resistance in crop cultivars. Theor. Appl. Genet. 102: 32-40.

Khan, J., L.E. del Rio, R. Nelson, V. Rivera-Varas, and G.A. Secor. 2008. Survival, dispersal, and primary infection site for *Cercospora beticola* in sugar beet. Plant Dis. 92: 741-745.

Khan, Q.A., and K.A. McVay. 2014. Impact of tillage, irrigation method, and nitrogen rate on sugar beet productivity. Agron. J. 106: 1717-1721.Kravchenko, A., R.E. Falconer, D. Grinev, and W. Otten. 2011. Fungal colonization in soils with different management histories: modelling growth in three-dimensional pore volumes. Ecol. Appl. 21: 1202-1210.

Licht, M., and M. Al-Kaisi. 2005. Strip-tillage effect on seedbed soil temperature and other soil physical properties. Soil Till Res. 80: 233–249.

Locke, M.A., and C.T. Bryson. 1997. Herbicide-soil interactions in reduced tillage and plant residue management systems. Weed Sci. 45: 307-320.

Maganti, M., S. Weaver, and M. Downs. 2005. Responses of spreading orach (*Atriplex patula*) and common lambsquarters (*Chenopodium album*) to soil compaction, drought, and waterlogging. Weed Sci. 53: 90-96.

Mahmoodi, R., H. Maralian, and A. Aghabarati. 2008. Effects of limited irrigation on root yield and quality of sugar beet (*Beta vulgaris* L.). Afr. J. Biotechnol. 7: 4475-4478.

Malik, A., A.S. Shakir, Naveedullah, M.J. Khan, M. Latif, K.S. Khattak, and T.A. Khan. 2018. Interactive effect of deficit irrigation and mulching on sugar beet productivity in Pakistan. Pak. J. Bot. 50: 1775-1783.

Martin, H.L. 2003. Management of soilborne diseases of beetroot in Australia: a review. Aust. J. Exp. Agr. 43: 1281-1292.

Milford, G.F.J., and J. Riley. 1980. The effects of temperature on leaf growth of sugar-beet varieties. Ann. Appl. Biol. 94: 431-443.

Miyazawa, K., T. Hiroyuki, M. Yamagata, H. Nakano, and T. Nakamoto. 2004. Response of soybean, sugar beet, and spring wheat to the combination of reduced tillage and fertilization practices. Plant Prod. Sci. 7: 77-87.

Monteith, J., and M. Unsworth. 2008. Principles of Environmental Physics (3rd edition), Elsevier, Amsterdam, The Netherlands, 418 pp.

Morris, N.L., P.C.H. Miller, J.H. Orson, and R.J. Froud-Williams. 2010. The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops, and the environment-a review. Soil Till Res. 108: 1-15.

Morse, R.D. 1999. No-till vegetable production—its time is now. Horttechnology 9: 373-379.

Nichols, V., N. Verhulst, R. Cox, and B. Govaerts. 2015. Weed dynamics and conservation agriculture principles: a review. Field Crop Res. 183: 56-68.

Oehrke, E.C., and H.W. Dehne. 2004. Safeguarding production- losses in major crops and the role of crop protection. Crop Prot. 23: 275-285.

Overstreet, L.F. 2009. Strip-tillage for sugarbeet production. Int. Sugar J. 111: 292-304.

Paulitz, T.C., R.W. Smiley, and R.J. Cook. 2002. Insights into the prevalence and management of soilborne cereal pathogens under direct seeding in the Pacific Northwest, USA. Can. J. Plant Pathol. 24: 416-428.

Payne, G.A., H.E. Duncan, and C.R. Adkins. 1987. Influence of tillage on development of gray leaf spot and number of airborne conidia of *Cercospora zeae-maydis*. Plant Dis. 71: 329-332.

Phillips, R.E., R.L. Blevins, G.W. Thomas, W.W. Frye, and S.H. Phillips. 1980. No-tillage agriculture. Science 208: 1108-1113.

Powell, G., C.R. Tosh, and J. Hardie. 2006. Host plant selection by aphids: behavioral, evolutionary and applied perspectives. Ann. Rev. Entomol. 51: 309-330.

Price, P.W. 1991. The plant vigor hypothesis and herbivore attack. Oikos 62: 244-251.

Rapp, H.S., R.R. Bellinder, H.C. Wien, and F.M. Vermeylen. 2004. Reduced tillage, rye residues, and herbicides influence weed suppression and yield of pumpkins. Weed Technol. 18: 953-961.

Röttger, V.U. 1979. Untersuchungen zur wirtswahl der rübenfliege *Pegomya betae* Curt. (Diptera, Anthomyidae). Z. Ang. Ent. 88: 97-107.

Röttger, V.U., and F. Klingauf. 1976. Änderung im stoffwechsel von zuckerrübenblättern durch befall mit *Pegomya betae* Curt. (Muscidae: Anthomyidae). Z. Ang. Ent. 82: 220-227.

Rotem, J., and J. Palti. 1969. Irrigation and plant diseases. Annu. Rev. Phytopathol. 7: 267-288.

Rousselin, A., M.H. Sauge, M.O. Jordan, G. Vercambre, F. Lescourret, and D. Bevacqua. 2016. Nitrogen and water supplies affect peach tree-green peach aphid interactions: the key role played by vegetative growth. Agr. Forest Entomol. 18: 367-375.

Ruppel, E.G. 1985. Susceptibility of rotation crops to a root rot isolate of *Rhizoctonia solani* from sugar beet and survival of the pathogen in crop residues. Plant Dis. 69: 871-873.

Rush, C.M., and S.R. Winter. 1990. Influence of previous crops on Rhizoctonia root and crown rot of sugar beet. Plant Dis. 74: 421-425.

Rytter, R.M. 2005. Water use efficiency, carbon isotope discrimination and biomass production of two sugar beet varieties under well-watered and dry conditions. J. Agron. Crop Sci. 191: 426-438.

Sainju, U.M., W.B. Stevens, R.G. Evans, and W.M. Iversen. 2013. Irrigation system and tillage effects on soil carbon and nitrogen fractions. Soil Sci. Soc. Am. J. 77: 1225-1234.

SAS Institute. 2017. SAS Procedures Guide, Version 9.4. SAS Institute, Cary, NC, USA.

Schweizer E.E., and M.J. May. 1993. Weeds and weed control. Pages 485-519 in Cooke D.A., Scott R.K., eds. The Sugar Beet Crop: Science into Practice. New York, NY: Chapman & Hall.

Scott, R.K., and S.J. Wilcockson. 1976. Weed biology and the growth of sugar beet. Ann. Appl. Biol. 82: 331-335.

Singh, M., M.S. Bhullar, and B.S. Chauhan. 2015. Influence of tillage, cover cropping, and herbicides on weeds and productivity of dry direct-seeded rice. Soil Till. Res. 147: 39-49.

Skaracis, G.N., O.I. Pavli, and E. Biancardi. 2010. Cercospora leaf spot disease of sugar beet. Sugar Tech 12: 220-228.

Sojka, R.E., E.J. Deibert, F.B. Arnold, and J. Enz. 1980. Sugarbeet production under reduced tillage- Prospects and problems. N. Dak. Farm Res. 38: 14-18.

Stevens, W.B., R.G. Evans, J.D. Jabro, and W.M. Iversen. 2010. Nitrogen availability for sugarbeet affected by tillage system and sprinkler irrigation method. Agron. J. 102: 1745-1752.

Stinner, B.R., and G.J. House. 1990. Arthropods and other invertebrates in conservation-tillage agriculture. Ann. Rev. Entomol. 35: 299-318.

Strausbaugh, C.A., and I.A. Eujayl. 2012. Influence of tillage systems on Rhizoctonia-bacterial root rot complex in sugar beet. Phytopathology 102: 115.

Sturz, A.V., M.R. Carter, and H.W. Johnston. 1997. A review of plant disease, pathogen interactions and microbial antagonism under conservation tillage in temperate humid agriculture. Soil Till. Res. 41: 169-189.

Sumner, D.R., B. Doupnik Jr., and M.G. Boosalis. 1981. Effects of reduced tillage and multiple cropping on plant diseases. Ann. Rev. Phytopathol. 19: 167-187.

Sumner, D.R., E.D. Threadgill, D.A. Smittle, S.C. Phatak, and A.W. Johnson. 1986. Conservation tillage and vegetable diseases. Plant Dis. 70: 906-911.

Sunderland, K.D., T. Blide, L.J.M.F. Den Nijs, A. Dinter, U. Heimbach, J.A. Lys, W. Powell, and S. Toft. 1996. Reproduction of beneficial predators and parasitoids in agroecosystems in relation to habitat quality and food availability. Act. Jutland. 71: 117-153.

Tarkalson, D.D., D.L. Bjorneberg, and A. Moore. 2012. Effects of tillage system and nitrogen supply on sugarbeet production. J. Sugar Beet Res. 49: 79-102.

Tarkalson, D.D., and B.A. King. 2017. Effect of deficit irrigation timing on sugarbeet. Agron. J. 109: 2119-2127.

Tonhasca, A., and B.R. Stinner. 1991. Effects of strip intercropping and no-tillage on some pests and beneficial invertebrates of corn in Ohio. Environ. Entomol. 20: 1251-1258.

Trevini, M., P. Benincasa, and M. Guiducci. 2013. Strip tillage effect on seedbed tilth and maize production in Northern Italy as case-study for the Southern Europe environment. Eur. J. Agron. 48: 50-56.

Wang, G.Y., and M. Ngouajio. 2008. Integration of cover crop, conservation tillage, and low herbicide rate for machine-harvested pickling cucumbers. Hortscience 43: 1770-1774.

Wrucke, M.A., and W.E. Arnold. 1985. Weed species distribution as influenced by tillage and herbicides. Weed Sci. 33: 853-856.

Zhang, H.H., Y.Q. Zhang, C.R. Yan, E.K. Liu, and B.Q. Chen. 2016. Soil nitrogen and its fractions between long-term conventional and no-tillage systems with straw retention in dryland farming in northern China. Geoderma 269: 138-144.