



Comparison of Fallow Tillage Methods in the Intermediate Rainfall Inland Pacific Northwest

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ABSTRACT

Winter wheat (*Triticum aestivum* L.) is usually grown in the Pacific Northwest (PNW) intermediate rainfall zone following tilled or chemical summer fallow. Studies were conducted near Davenport, WA and Helix, OR over two fallow–winter wheat cycles to evaluate the efficacy of reduced or no-tillage fallow compared to conventional fallow and compare the efficacy of herbicides applied using a light-activated sensor-controlled (LASC) applicator to broadcast applications. Six treatments included conventional primary tillage followed by rodweeding; sweep-tillage followed by rodweeding, broadcast, or LASC herbicide application; and no-tillage followed by broadcast or LASC herbicide application. Broadcast and LASC herbicide applications controlled weeds similarly in no-tillage treatments. However, LASC applications used from 45 to 70% less herbicide than broadcast applications to attain similar weed control. No-tillage or sweep-tillage systems with herbicide application had from 15 to 30% greater surface residue cover than the conventional tillage system. Available soil moisture in both the root-zone and seed-zone soil profiles at time of planting was similar among tillage systems. There were no differences in wheat quality parameters across treatments. The conventional tillage system had similar wheat grain yield as sweep-tillage systems followed by rodweed or broadcast herbicide application, but yields were up to 21% greater than sweep-tillage with LASC applied herbicides and no-tillage systems. Reduced tillage systems using sweep-tillage and broadcast herbicide application could potentially replace more tillage intensive fallow systems in the PNW.

THE INTERMEDIATE RAINFALL ZONE of the inland PNW comprises 620,000; 323,000; and 25,000 ha of dryland cropping in Washington, Oregon, and Idaho, respectively (Schillinger et al., 2006). The region is characterized by an average annual rainfall of 300 to 450 mm. Winter wheat/summer fallow or winter wheat/spring wheat/summer fallow rotation is the main cropping system of this area (Juergens et al., 2004). Generally, winter wheat is grown following a year of fallow, which is necessary to recharge soil with sufficient moisture for crop growth and development (Papendick, 1998). In spite of long-term efforts, researchers have not developed sustainable annual-cropping systems to replace summer fallow cropping systems in this region (Nail et al., 2005). In the absence of tillage, a major portion of soil moisture recharge from fall and winter precipitation is lost during the summer due to capillary flow/evaporation from soil or transpiration by weeds. A study in Australia by Freebairn et al. (1986) reported that evaporation reduced soil moisture 65% in the absence of tillage during the summer fallow period. Summer fallow tillage systems have been developed to break the capillary continuity between subsoil and

surface soil by creating a dust mulch barrier at the soil surface to reduce evaporation losses and conserve moisture in the seed zone (Al-Mulla et al., 2009). However, these tillage practices degrade soil physical properties and pose a threat of increased soil erosion from wind and water. Moreover, air-borne soil particles, generated during fallow tillage and subsequent wind driven soil erosion, endanger human health (Papendick, 1998, 2004), and decrease soil productivity (Tanaka, 1989; Saxton, 1995; Larney et al., 1998; Sorenson, 2000; Saxton et al., 2000).

In dryland farming of the PNW, conservation tillage practices, particularly minimum tillage and a delayed minimum tillage system described by Schillinger (2001), have been shown to be profitable and environmentally friendly. Conservation tillage is defined as a management practice that leaves >30% of the previous crop's residues on the soil surface after planting by omitting or reducing the intensity of at least one major tillage operation (Locke and Bryson, 1997). Both minimum tillage and delayed minimum tillage systems rely on non-inversion implements such as an undercutter cultivator to reduce the intensity of soil movement in primary tillage operations. Nonselective herbicides may be used for weed control following primary tillage, but more typically, secondary tillage such as rod weeding is employed. Delayed minimum tillage is similar to minimum tillage, but the use of an undercutter cultivator as the primary tillage is delayed until at least mid-May. The undercutter cultivator, comprised of wide (~75 cm) V-shaped blades or sweeps, is an important component of conservation tillage summer fallow systems and is usually followed by two or more rod weeding operations later in the fallow period for weed control or residue management. Undercutter cultivator operations, as part of a conservation tillage program, reduce production

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Abbreviations: LASC, light-activated sensor-controlled sprayer; NIS, non-ionic surfactant; PNW, Pacific Northwest; UAN, urea ammonium nitrate.

costs (Weersink et al., 1992) while increasing soil surface residue cover and surface roughness compared to conventional mechanical dust mulch summer fallow systems (Schillinger, 2001). Greater crop residue coverage in conservation tillage systems can increase soil water infiltration and storage (Hatfield et al., 2001), and reduce soil water evaporation (Schillinger and Bolton, 1993), seed-zone soil moisture loss (Griffith et al., 1986; Aase and Pikul, 1995; Uri, 1998), and soil erosion (Ramig and Ekin, 1987) during the fallow period. Zaikin et al. (2007) and Nail et al. (2007) reported the undercutter cultivator or sweep-tillage fallow system to be more profitable than conventional dust mulch fallow systems, providing similar wheat yields at reduced cost of production. Moreover, under current economic conditions, lower fuel (Janosky et al., 2002; Nail et al., 2007) and farm labor (Young et al., 2008) expenses have made conservation tillage more profitable than conventional tillage systems for winter wheat/summer fallow.

Chemical fallow (no-tillage) is a form of conservation tillage in which all preplant tillage is omitted and the crop is direct-seeded following weed control with nonselective herbicides such as glyphosate (*N*-(phosphonomethyl) glycine) or paraquat (1,1'-dimethyl-(4,4'-bipyridinium) cation). Bennett and Pannell (1998) reported that the sparse patchy nature of weed distribution often results in deposition of most of the broadcast herbicide application on bare soil rather than on weed foliage. Thus, effective spot treatment application of herbicides in no-tillage, even with greater effective rates, could result in substantial cost savings, reduced herbicide use, and improved weed control compared to broadcast applications. To date, efficient spot applications of herbicides to fields have not been practical due to the lack of effective automated equipment or the need for great technical expertise by the operator. However, the introduction of real-time LASC sprayers has resulted in more accurate and precise spot applications of herbicides (Biller, 1998) and could be used in no-tillage systems to reduce the amount and area of applied herbicides. The LASC sprayers are comprised of light sensors for red and near infrared wavelengths (Felton and McCloy, 1992). At red and near infrared wavelengths, soil and green plants reflect ambient light at ratios of 1.1:1.5 and 6:15, respectively. The differential reflection allows LASC sprayers to detect plants and activate a solenoid switch above a spray nozzle for a set period of time (Biller, 1998). The LASC sprayers used for directed postemergence weed control in crop have shown reductions in herbicide cost of nearly 25% compared to broadcast sprayer, with no reduction in crop yield (Dammer and Wartenberg, 2007). Other researchers have shown that LASC sprayers have reduced herbicide use ranging from 30 to 70% compared to broadcast applications in chemical fallow (Ahrens 1994; Biller, 1998; Blackshaw et al., 1998) and row crops (Hanks and Beck, 1998). Recently, Young et al. (2008) reported similar postharvest Russian thistle (*Salsola tragus* L.) control with herbicide reductions of 42% using a LASC sprayer compared to a broadcast application, resulting in savings of \$6.68 to \$18.21 ha⁻¹. Even with these positive results, growers have yet to fully use LASC applicators for no-tillage and other systems due to high equipment investment cost and a lack of efficacy information in various cropping systems.

To compare summer fallow systems for the PNW intermediate rainfall area, a study was conducted with the following objectives: (i) investigate methods of conservation tillage in summer fallow that use sweep-tillage, no-tillage fallow, or

combinations of minimum tillage with herbicides compared to conventional dust-mulch systems and (ii) evaluate weed control efficacy of a LASC sprayer compared to broadcast sprayer applications in chemical fallow systems.

MATERIALS AND METHODS

Research was conducted over two fallow–winter wheat cropping cycles (2007–2008 and 2008–2009) at the Washington State University Wilke Research and Extension Farm, Davenport, WA (47°39' N, 118°7' W, 756 m altitude) and on a commercial dryland wheat farm, near Helix, OR (45°57' N, 118°47' W, 540 m altitude). Both Davenport and Helix locations had a cereal/summer fallow rotation in place for several years preceding the current study and had long-term annual precipitations of 377 and 320 mm, respectively. Soil types were a Broadax silt loam (fine-silty, mixed, superactive, mesic Calcic Argixeroll) and Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxeroll) at the respective locations. The soil properties across locations and years are provided in Table 1. Monthly and annual precipitation recorded at nearby (<5 km) weather stations over the period of the study at both locations are reported in Table 2.

Experimental Plot Establishment and Tillage Treatments

Each year, all experiment sites received a broadcast application of glyphosate at 840 g a.e. ha⁻¹ (April and May at Helix and Davenport, respectively) to kill weeds and volunteer wheat, which is a standard operation in the area before establishing summer fallow. Experiments were laid out in a randomized complete block design with six treatments and four replications. The six fallow treatments included (i) sweep-tillage followed by broadcast herbicide application (sweep/broadcast), (ii) sweep-tillage followed by LASC herbicide application (sweep/LASC), (iii) no-tillage followed by broadcast herbicide application (no-till/broadcast), (iv) no-tillage followed by LASC herbicide application (no-till/LASC), (v) sweep-tillage followed by rodweeding (sweep/rodweed), and (vi) conventional tillage with disc or chisel followed by rodweeding (conventional). Experimental plots were 4.5 m wide by 31.0 m long at Davenport during 2007–2008. However, to facilitate rodweeding operations, the plot width was increased to 9.0 m for 2008–2009. At Helix, experimental plots were 12.0 m wide by 99.0 m long each year. A detailed list of field operations and their timing for individual treatments is shown in Table 3. Plots were mechanically packed following sweep cultivation in sweep-tillage with broadcast or LASC spray treatments at both locations. A roller (30 cm diam.) and a coil packer (45 cm wheel diameter) were used for soil packing at Davenport and Helix, respectively. Fertilizer was applied at 85 kg N ha⁻¹ to all treatments in the manner described in Table 3.

Herbicide Treatments

In June at both locations, glyphosate (Roundup Original Max, Monsanto Co., St. Louis, MO) at 1680 g ha⁻¹ was applied using a broadcast or LASC sprayer to the respective treatments under the conditions described in Table 3. At Davenport, the LASC sprayer system consisted of 15 individual LASC units (WeedSeeker, N'Tech Industries, Ukiah, CA), fitted with Teejet 6504 flat-fan nozzles (30 cm apart and operated at a height of 60 cm), and mounted on a 4.5-m wide

Table 1. Soil properties, application dates and conditions for herbicide treatments during 2007 and 2008 fallow period at Davenport, WA, and Helix, OR.

		Davenport, WA		Helix, OR	
		2007	2008	2007	2008
Soil properties	pH	5.2	5.0	5.7	6.3
	organic matter, %	3.0	2.9	1.3	1.4
	CEC, cmol kg ⁻¹	21.0	19.0	13.3	12.7
Soil texture	sand, %	30.0	28.8	31.9	29.3
	silt, %	58.8	61.2	62.1	60.9
	clay, %	11.2	10.0	6.0	9.8
Crop stubble		spring wheat	spring barley	winter wheat	winter wheat
LASC/Broadcast application dates		3 July 2007	9 July 2008	28 June 2007	2 July 2008
Application conditions during LASC/Broadcast herbicide treatments	air temperatures, °C	31	29	21	27
	relative humidity, %	21	24	48	46
	wind, km h ⁻¹	6	2	10	3
	cloud cover, %	10	5	30	30
	soil temperature (°C at 10- cm depth)	22	20	14	21
Weed height at the time of treatment	tumble pigweed	2–12 cm	10–15 cm	np	np
	prickly lettuce	np†	np	10–30 cm	10–50 cm
	Russian thistle	12–25 cm	np	10–25 cm	7–30 cm

† np = Weed species not present.

boom. Broadcast applications at Davenport were made using the same sprayer and setup using the continuous spray setting. The LASC sprayer was calibrated to deliver 187 L ha⁻¹ at 260 kPa on a broadcast basis. At Helix, the LASC sprayer system consisted of 10 similar LASC units mounted on a 3-m wide boom (30 cm spacings and operated at a height of 60 cm). The LASC sprayer at Helix was calibrated to deliver 224 L ha⁻¹ at 240 kPa on a broadcast basis. A separate conventional tractor-mounted broadcast sprayer with a 2.7-m wide boom and XR-8002 flat fan nozzles (45 cm spacing, and operated at a height of 60 cm) calibrated to deliver 150 L ha⁻¹ at 260 kPa, was used for broadcast applications at Helix. At both locations, the LASC spray system was connected to a tractor-battery operated control box and regulated CO₂ supply tank for system pressure. All pressure and sprayer volumes described above were consistent over both years within a location. Application dates and conditions are listed in Table 1. Since the process of sensor calibration is critical to the accuracy of weed detection by the LASC sprayer operation and resulting herbicide use, the LASC sprayer control box was set at medium sensitivity and

sensors were calibrated for the background base of soil and crop residue before spraying each individual plot. For LASC sprayer applications in sweep/LASC and no-till/LASC systems, 5.7- and 3.0-L spray solutions were mixed for individual plots at Davenport and Helix, respectively. The amount of spray solution remaining following the application to an individual plot was measured and subtracted from the original mix amount to determine the spray volume and amount of herbicide applied to the respective plot. Data from the four replications of a treatment were averaged to calculate spray volume and herbicide used by LASC sprayer for each treatment. The sweep/broadcast and no-till/broadcast treatments were broadcast sprayed with glyphosate at 1680 g ha⁻¹. The actual amounts of herbicide used in the LASC applied treatments were compared to the estimated amount of spray solution used in a broadcast application. These estimates were calculated based on the sprayer output and the area covered by a broadcast application. At Davenport, weed densities were recorded by species from four random 0.25 m² quadrates per plot in each treatment before herbicide application or rodweeding. Additionally, weed

Table 2. Monthly and annual precipitation during study period at Davenport, WA, and Helix, OR.

Month	Davenport, WA				Helix, OR			
	2006–2007	2007–2008	2008–2009	57 yr avg.	2006–2007	2007–2008	2008–2009	30-yr avg.
precipitation, mm								
Sept.-Feb.	252.1	235.5	113.5	222.0	185.0	133.9	107.7	186.8
Mar.	23.0	35.3	33.3	36.1	25.2	20.7	71.1	31.0
Apr.	18.9	23.7	17.8	26.9	16.8	6.7	20.7	27.5
May	33.1	17.0	29.2	35.3	7.2	36.1	22.0	31.3
June	17.7	25.9	26.7	26.4	22.0	13.3	7.2	20.0
July	6.1	0.0	10.4	16.5	3.2	0.0	0.0	10.0
Aug.	18.1	9.4	18.3	14.5	6.2	6.9	18.5	14.0
Annual	369.0	346.9	249.2	377.7	265.5	217.6	247.2	320.5

Table 3. Timeline of field operations and applications of individual treatments for each fallow–winter wheat crop cycle at Davenport, WA, and Helix, OR.

Month	Treatment					
	Sweep/broadcast	Sweep/LASC†	No-till/broadcast	No-till/LASC	Sweep/rodweed	Conventional
Apr.	Broadcast application of glyphosate at 840 g a.e. ha ⁻¹ to kill weeds and volunteer wheat					
May	Primary tillage with sweep undercutter at 12-cm depth + fertilization with injection of UAN solution (at 85 kg N ha ⁻¹ and 12-cm depth with undercutter) + roller packer at Davenport and coil packer at Helix			Primary tillage with sweep undercutter at 12-cm depth+ fertilization with injection of UAN (32%) at 85 kg N ha ⁻¹ and 12-cm depth with undercutter		Primary tillage with tandem disk (two passes) at 12-cm depth, followed by fertilization with surface broadcast application of urea with hand at 85 kg N ha ⁻¹ . At Davenport in 2007–2008, this treatment was fall chisel plowed to a depth of 12 cm with single disking in the spring.
June	Application of glyphosate at 1680 g a.e. ha ⁻¹ with LASC or broadcast sprayer as appropriate			First rod weeding at 10-cm depth. Not required in 2008 at Davenport, so first rodweeding was delayed until July.		
July	Follow-up rod weeding at 10 cm depth					
Aug.	Recorded weed density and biomass					
	Applied glyphosate at 1680 g a.e. ha ⁻¹ if necessary before winter wheat planting			Preplant rod weeding at 10 cm depth		
	Wheat harvesting for the crop following fallow treatments					
Sept.‡	Soil moisture sampling; seed-zone and 1.5 m deep soil profile					
	Winter wheat seeding + fertilization in no-till/Broadcast and no-till/LASC with seed planter (urea at 85 kg N ha ⁻¹)					
Oct.	Winter wheat emergence measured					
Nov.	Soil surface residue cover measurement					

† Abbreviations: LASC, light-activated sensor controlled sprayer; UAN, urea ammonium nitrate.

‡ Winter wheat in no-tillage treatments at Helix was planted in first week of November during 2008 and emergence count made in first week of December 2008.

density and biomass were recorded from random 5- and 1-m² areas per plot in July and August at Helix and Davenport, respectively, each year to determine treatment efficacy before the preplant herbicide application or tillage.

Soil Sampling

Broadcast and LASC herbicide applications were assumed to be the same within the sweep and no-tillage regimes. Consequently, for no-tillage and sweep-tillage treatments, soil moisture samples were only collected from plots that received broadcast herbicide applications. Three 150-cm deep (root-zone) soil cores and one core for 30-cm deep (seed-zone) soil profile were collected from random locations in each plot to determine soil moisture content before winter wheat planting. The 150-cm deep soil cores were collected using a tractor mounted-hydraulic soil sampling machine model GSRTS (Giddings Machine Co., Inc., Windsor, CO), and seed-zone soil cores were collected manually. Individual soil cores for 150-cm deep profile were separated into five 30-cm sections. At Davenport in 2007, soil cores were collected to a depth of 120 cm due to problems getting a consistent deeper sample. The sampling tube used at both locations had 5 and 4.7 cm outer diameter (o.d.) and inner diameter (i.d.), respectively, and 4.0 cm i.d. cutting edge. The soil sampling probe for seed-zone soil moisture had 5.1 and 4.6 cm o.d. and i.d., respectively, along with a 4.5 cm i.d. cutting edge. At Davenport in 2008 and Helix in both years, seed-zone cores were divided into increments of 0- to 3-, 3- to 5-, 5- to 7-, 7- to 9-, 9- to 11-, 11- to 13-, 13- to 15-, 15- to 20-, 20- to 25-, and 25- to 30-cm depth increments using a small-increment electric soil sampler (Wuest and Schillinger, 2008) for a total of 10 sampling increments per plot. At Davenport during 2007, a sampling probe with 1.9 cm i.d. was used to take three random 30-cm deep seed-zone soil cores per plot. These cores were divided into 0- to 5-, 5- to 10-, 10- to 15-, 15- to 20-, 20- to 25-, and 25- to 30-cm depth increments. The weight of soil at each increment was recorded individually for each of the three cores taken per plot. Soil was

dried at 105°C for 48 h to determine dry weight of individual soil increments. Percent soil moisture on a gravimetric basis (% soil moisture) was determined using Eq. [1].

$$\% \text{ SM} = (\text{fwt} - \text{dwt}) / \text{dwt} \times 100 \quad [1]$$

where % SM is percent of gravimetric soil moisture on a dry wt. basis, fwt is the initial weight of the soil core following drying, and dwt is the weight following drying. For statistical analysis, the soil moisture contents of the three cores taken from the same plot were averaged for individual increments.

Winter Wheat Planting and Emergence, and Previous Crop Residue Cover

Following soil moisture sampling, winter wheat was sown in September in each year and location, with the following exceptions. In 2007 at Helix, several plots in the no-till fallow treatments were reseeded due to poor initial wheat emergence. Additionally, due to dry soil conditions in the fall of 2008, winter wheat sowing in no-tillage treatments at this location was delayed until November when soil moisture in seed-zone was adequate for germination following late fall precipitation. At Davenport, soft white winter wheat (cultivar ORCF 102) was planted at 80 kg ha⁻¹ to a depth of 5 cm and row spacing of 25 cm. At Helix, hard red winter wheat (50/50 mixture of cultivars Boundary and Elious) was planted at 100 kg ha⁻¹ to a depth of 5 cm each year. At Helix, conventional and sweep-tillage treatments were seeded in 40-cm row spacing with a deep-furrow drill model JD-HZ616 (Deere and Co., Moline, IL) while no-tillage treatments were seeded in a row spacing of 25 cm, and seeded with a hoe-type, Great Plains 4010 no-till drill (Western Equip. LLC., Alva, OK). Crop emergence was measured in October or November of each year at each location by counting the number of plants within five random 1-m row lengths in each plot. Emergence count was calculated as plants m⁻² before analysis to account for differences

Table 4. Mean percent crop residue in different tillage treatments during two winter wheat–fallow cycles at Davenport, WA, and Helix, OR.

Treatment	Davenport, WA	Helix, OR
	% residue cover	
Conventional	69.33	33.75
Sweep/rodweed	77.33	37.00
Sweep/broadcast	85.84	43.00
Sweep/LASC†	81.88	41.88
No-till/broadcast	88.20	43.63
No-till/LASC	92.71	48.00
LSD ($P \leq 0.05$)	11.56	10.43

† Abbreviations: LASC, light-activated sensor-controlled sprayer.

in row spacing of the individual treatments. Percent crop residue cover was measured in November or December of each year following wheat emergence. However, the residue cover measurement for the 2007–2008 fallow–winter wheat cycle was delayed at Davenport until 8 Apr. 2008 due to early and prolonged snow cover on the study site. To determine residue cover, digital photographs of three random 0.25 m² quadrates per plot were taken from a constant height of 1 m. The area in each photograph within the quadrate was superimposed onto a 100-point grid. Percent crop residue was calculated by counting the number of grid points that intersected crop residue in the photograph.

Weed Control in Winter Wheat

Weed species composition and density in the winter wheat crop were determined in May of 2008 and 2009 by counting the number of weeds of each species within four random 0.25 m² quadrates per plot. At Davenport, weeds were completely controlled following these counts with application of 35 g a.e. ha⁻¹ imazamox (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-(methoxy-methyl)-3-pyridinecarboxylic acid) mixed with 310 g a.i. ha⁻¹ pyrasulfotole ((5-hydroxy-1,3-dimethyl-1H-pyrazol-4-yl)[2-(methylsulfonyl)-4-(trifluoromethyl)phenyl]methanone) plus 250 g a.i. ha⁻¹ bromoxynil (3,5-dibromo-4-hydroxybenzotrile), urea ammonium nitrate solution (UAN, 2.5% v/v) and non-ionic surfactant (NIS, 0.25%, v/v). At Helix, broadleaf and grass weed control in winter wheat was attained following weed count in May with an application of 4.2 g a.i. ha⁻¹ metsulfuron (2-[[[[[4-methoxy-6-methyl-1,3,5-triazin-2-yl]amino]carbonyl]amino]sulfonyl]benzoic acid) plus 380 g a.e. ha⁻¹ 2,4-D ((2,4-dichlorophenoxy)acetic acid) and a separate application of 17 g a.i. ha⁻¹ propoxycarbazone (methyl 2-[[[[4,5-dihydro-4-methyl-5-oxo-3-propoxy-1H-1,2,4-triazol-1-yl]carbonyl]amino]sulfonyl]benzoate) plus 110 g a.i. ha⁻¹ mesosulfuron-methyl (Methyl 2-[[[[[4,6-dimethoxy-2-pyrimidinyl]amino]carbonyl]amino]sulfonyl]-4-[[[(methylsulfonyl)amino]methyl]benzoate). At Helix, all herbicide solutions used for weed control in winter wheat contained NIS (0.25% v/v).

Winter Wheat Yield and Protein Content

Wheat grain yield was determined by harvesting two 1.5-m swathes across the entire length of each plot at Davenport using a small plot harvester (Kincaid Seed Res. Equip. Manuf., Haven, KS) while entire plots were harvested at Helix using a commercial-size JD 9770 combine (Deere and Co., Moline, IL). At Davenport, all harvested grain from each plot was collected in bags, cleaned with a Clipper mill and weighed to determine yield. At Helix,

all harvested grain from each plot was transferred in the field to a stationary wagon equipped for weighing. Subsamples of wheat grain were used to determine the percent protein content for both locations. The protein content was determined by the AACC International (2000) approved near-infrared spectroscopy (NIRS) method 39–11 (Davies and Berzonsky, 2003).

Statistical Analyses

Data were subjected to ANOVA using PROC MIXED in SAS (SAS Institute, 2005) and sum of squares were partitioned to evaluate the effect of treatment, year, and location on weed density, weed biomass, percent gravimetric soil moisture, winter wheat emergence, crop residue, grain yield, and grain protein. Before analysis, data were tested for normality and homogeneity of variance using PROC UNIVARIATE. Mean separations were performed on data using Fisher's protected least significant difference (LSD) test at p values ≤ 0.05 . Mean separations were calculated using pdiff option and PDMIX 800 macro with PROC MIXED (Saxton 1998). Data analysis indicated significant treatment \times year \times location interactions for soil moisture, yield, and quality parameters, thus data are presented by years and locations. During the summer fallow period, different weed species emerged at Davenport and Helix (Table 1) and interactions existed among years and treatments for weed density and biomass. Therefore data for weed density and biomass are also presented separately for years and locations. There was no treatment \times location, treatment \times year, or treatment \times location \times year interaction for surface crop residue, but conventional tillage and sweep-tillage treatments had different row-spacing at Davenport and Helix. Thus, data for percent crop residue are presented by locations averaged over years.

RESULTS AND DISCUSSION

Crop Residue

Percent crop residue cover in summer fallow systems ranged from 69 to 93% and 34 to 48% at Davenport and Helix, respectively (Table 4). At Davenport, there was substantial residue remaining from the previous spring wheat and spring barley crops each year. At Davenport, conventional tillage system had least residue cover of all other systems, but had residue cover similar to sweep/rodweed. At Helix, there was less crop residue cover compared to Davenport due to wider row spacing and lower crop productivity (because of less annual rainfall, Table 2). At Helix, the crop residue cover in the conventional tillage system was less than only no-till/LASC; however, the trend was similar to that observed at Davenport. Likely, the previous crop residue in conventional tillage systems was finely divided by the disk/chisel and more rapidly degraded compared to the intact aboveground residue remaining following sweep- and no-tillage systems. Tanaka (1986) also reported more rapid degradation of winter wheat and spring wheat surface residue in conventional compared to no-tillage fallow. Overall, conventional fallow resulted in reduced residue cover compared to sweep-tillage systems with herbicide spray and no-tillage systems at both locations. Schillinger (2001) reported 11 to 64% greater surface residue in sweep-tillage compared to conventional tillage systems. Fenster et al. (1969) also reported 25% greater crop residue in sweep tilled compared to disk-tilled fallow systems.

Table 5. Weed density and biomass after herbicide or rodweeding applications in different tillage treatments at Davenport, WA, and Helix, OR during fallow period of years 2007–2008 and 2008–2009†.

Treatment	Davenport, WA				Helix, OR			
	2007		2008		2007‡	2008		
	AMAAL	AVEFA+BROTE	Total biomass	AMAAL	Total biomass	SASKR	LACSE	SASKR
	plants m ⁻²	g m ⁻²	plants m ⁻²	g m ⁻²		plants m ⁻²		g m ⁻²
Conventional	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sweep/rodweed	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00
Sweep/broadcast	2.01	0.36	12.19	0.12	0.41	0.09	0.02	0.10
Sweep/LASC	1.80	0.11	17.89	0.09	1.06	2.50	0.27	1.20
No-till/broadcast	1.84	0.36	6.20	0.04	0.12	0.05	0.73	0.02
No-till/LASC	1.32	0.53	13.65	0.04	0.24	0.50	1.45	0.32
LSD ($P \leq 0.05$)	1.59	0.34	11.34	0.05	0.65	0.65	0.41	0.69

† Abbreviations: AMAAL, tumble pigweed; AVEFA, wild oat; BROTE, downy brome; LASC, light-activated sensor controlled sprayer; LACSE, prickly lettuce; SASKR, Russian thistle.

‡ Total weed biomass was not recorded at Helix during fallow period of year 2007–2008.

Weed Density and Biomass

In all locations and years, conventional and sweep/rodweed systems were kept weed-free with timely rodweeding following new flushes of weeds which resulted in almost complete control of weeds at the end of the fallow period (Table 5). At Davenport in 2007, tumble pigweed (*Amaranthus albus* L.) densities were similar in all nonrodweeded systems, but sweep/LASC system had greater weed biomass compared to no-till/broadcast system. Similarly, the greatest tumble pigweed densities and biomass were observed in sweep/broadcast and sweep/LASC systems, respectively, at Davenport in 2008. In contrast to tumble pigweed control, the LASC sprayer provided better control of wild oat (*Avena fatua* L.) and downy brome (*Bromus tectorum* L.) in sweep-tillage compared to no-tillage systems at Davenport in 2007, which was likely due to the failure of the LASC sprayer to detect very small weeds that were fully or partially obscured under heavy surface crop residue of no-tillage systems (Table 4). All treatments controlled grass weeds similarly at Davenport during 2008 (data not shown) where there were no differences in residue cover among sweep- and no-tillage systems. Similar results were observed at Helix, where Russian thistle densities were greater in the sweep/LASC system compared to other systems during each year (Table 5).

Airborne dust churned up by the LASC and broadcast spray tractors may have reduced control of tumble pigweed and Russian thistle in the tire tracks compared to elsewhere at both locations (authors' personal observation). Previous studies (Mathiassen and Kudsk, 1999; Zhou et al., 2006) have reported reduced efficacy of glyphosate when applied during dusty conditions. Blackshaw et al. (1998) and Young et al. (2008) also expressed concerns about reduced weed control efficacy of LASC sprayers operated in dusty conditions. The reduced detection of very small weeds by LASC sprayer in dusty conditions was likely due to dust accumulation on the light sensors or dispersion of light through airborne dust particles. Moreover, sweep-tillage resulted in a visible increase in tumble mustard and Russian thistle density compared to no-till, due to probable differences in soil disturbance (authors' personal observation). Therefore, each year at Davenport and Helix, the reduced tumble pigweed and Russian thistle control, respectively, in sweep/LASC system compared to no-tillage systems was due to the greater weed densities before spray in sweep-tillage systems, reduced tumble pigweed control by glyphosate in dry and dusty conditions, and/or reduced detection of very small weeds by LASC

sprayers under dry dusty conditions (Mathiassen and Kudsk, 1999; Zhou et al., 2006; Young et al., 2008).

At Helix, prickly lettuce (*Lactuca serriola* L.) densities for LASC and broadcast applications were similar across all respective treatments during 2007 (data not shown). However, greater prickly lettuce emergence in no-tillage compared to sweep-tillage systems (authors' personal observation) along with potentially reduced ability of the LASC sprayer to detect very small weeds during dry and dusty conditions resulted in greater prickly lettuce densities in no-till/LASC than no-till/broadcast systems at Helix during 2008 (Table 5). Weed biomass was not recorded in 2007 and was recorded as total of all species in 2008 at Helix. Total weed biomass at Helix in 2008 was greater in sweep/LASC system compared to other systems primarily due to greater Russian thistle densities in those treatments. The broadcast and LASC systems had similar total weed biomass under no-tillage systems at Helix in 2008. Weeds were effectively controlled in the winter wheat by the in-crop herbicide applications in all systems, years, and locations (data not shown).

Herbicide Use

The LASC applications used 45 and 55% less glyphosate than broadcast applications at Davenport in Year 1 and Year 2, respectively, and 60 and 72% less at Helix in the same respective years. Previous research has shown similar herbicide use reductions with LASC sprayer technology compared to broadcast herbicide applications (Ahrens, 1994; Biller, 1998; Blackshaw et al. (1998), Young et al., 2008). With the 45 to 70% reduction in herbicide loading per unit area by LASC sprayers as measured in this and other studies, increasing the herbicide broadcast rate equivalent applied through LASC sprayers is a possible method to improve the efficiency of LASC sprayers in dusty and dry conditions while still reducing net herbicide load.

Soil Moisture

The percent gravimetric soil moisture content in 30-cm (seed-zone) and 150-cm soil profiles varied across locations and there were significant treatment \times year \times location interactions for soil moisture. Thus, data are presented separately for years and locations. At Davenport in 2007, there were no significant differences in fallow soil moisture among treatments to depths of 90 cm (Fig. 1A). However, no-till/broadcast system had 23% less moisture than sweep/broadcast system in the 90 to 120 cm soil profile. During 2008 at

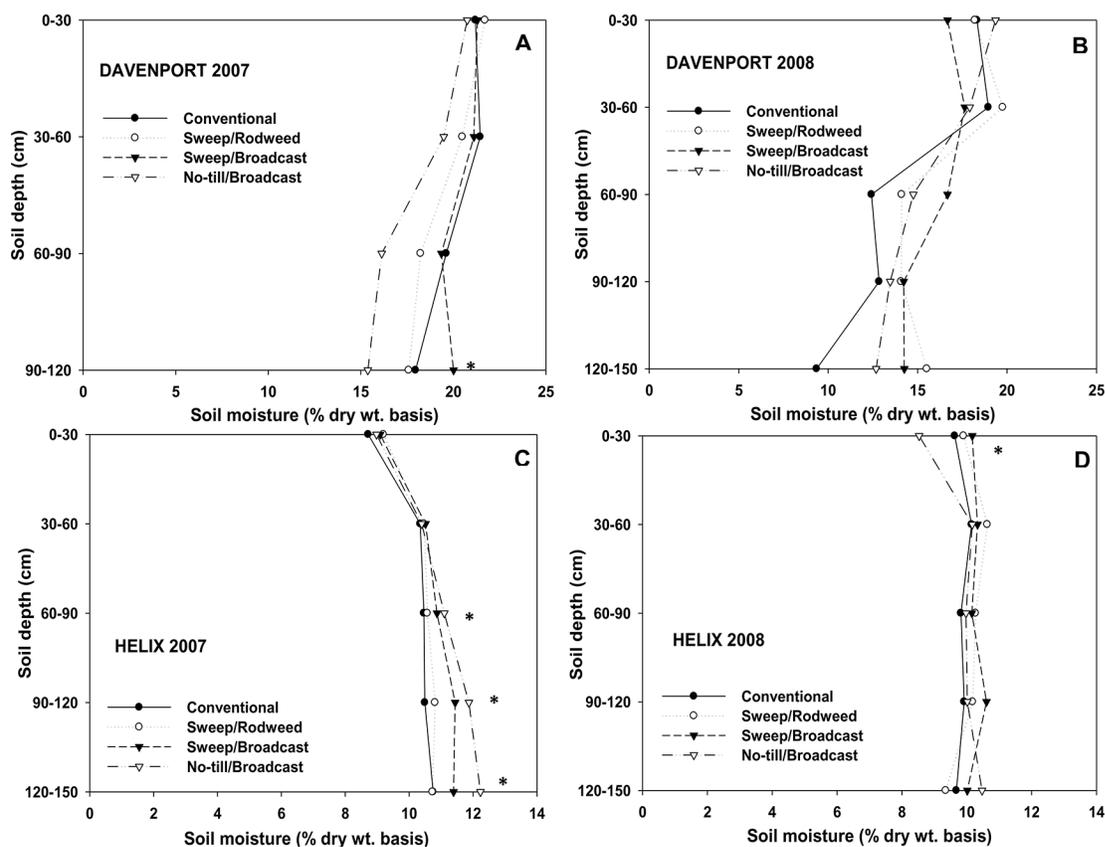


Fig. 1. A–D. Gravimetric soil moisture (% dry wt. basis) content in 150-cm deep soil profile at (A) Davenport, WA–2007 (B) Davenport, WA–2008 (C) Helix, OR–2007, and (D) Helix, OR–2008 fallow periods. * Represents significant difference ($P < 0.05$) between one or more treatments at respective depths. Measurements were made before winter wheat planting on 1 and 5 September for 2007 and 2008, respectively, at Davenport, and 24 and 26 August for the same respective years at Helix.

Davenport, there were no significant differences in soil moisture among treatments at any depth (Fig. 1B). Rainfall in the summer of 2008 (May–August) was 30% less than 2007 (Table 2). Therefore, soil moisture between fallow systems in the deeper profiles did not differ in 2008 (Fig. 1B). The difference in seed-zone soil moisture among tillage systems at Davenport existed only for the top 5 cm soil profile in each year (Fig. 2A and B). Rainfall 2 wk before sampling confounded the results in 2007, where top 5 cm soil profile of conventional tillage system showed greater moisture compared to sweep/broadcast system. However, because of the loosening of the top soil by the rodweeder, conventional tillage and sweep/rodweed systems contained less moisture in upper 3 cm soil compared to sweep/broadcast and no-till/broadcast systems during 2008. Never-the-less, seed-zone moisture at depth of planting (~9–11 cm) was similar in all systems at Davenport in 2007 and 2008.

At Helix, a lower-rainfall site compared to Davenport, both 150 cm and seed-zone soil profiles had less moisture compared to Davenport (Fig. 1 and 2). At Helix in 2007, the top 60 cm soil profile had very low moisture in all the systems due to extremely dry conditions before wheat planting (Fig. 1C). The seed-zone moisture at Helix in 2007 was less than necessary for optimum wheat seed germination; therefore, a deep-furrow drill was needed to place seed to depths with moisture in conventional and sweep-tillage systems. The deep-furrow drill used in this study (JD HZ) does not work well in high residue seedbeds such as found in no-till. Therefore, no-till plots were seeded using an appropriate no-till drill. However, the resulting poor initial crop emergence in 2007 no-tillage systems (data not shown) due to shallow planting

necessitated the reseeded for those treatments at a later date.

For the wheat crop harvested at Helix in 2008, the total annual precipitation was even less than 2007 (Table 2), thus both 150 cm soil profile and seed-zone soil profile were dry. In 2008 at Helix, no-tillage had less moisture content in top 30 cm soil profile compared to sweep-tillage systems (Fig. 1D). Schillinger and Bolton (1993) also found that no-tillage systems lose more moisture in the top layer of soil due to upward capillary flow of water. Because of the very low seed-zone moisture at Helix in 2008, the deep-furrow drill was again used in conventional and sweep-tillage plots in September. However, seed could not be placed deep into moisture with the no-till drill and thus seeding in no-till plots was delayed until November following precipitation.

Wheat Yield and Quality

Winter wheat emergence was similar in each system at Davenport both years, while at Helix different emergence among no-tillage and other systems was due to seeding of no-tillage plots later after rainfall. Thus winter wheat emergence data are not shown. Wheat grain yields were similar in all tillage systems at Davenport in the 2007–2008 crop year, but rodweeded systems tended to have greater yields compared to other systems (Table 6). Generally, wheat grain yields in all the treatments at Davenport were lower in 2007–2008 compared to 2008–2009 due to a comparatively cold winter. During 2008–2009 at Davenport, winter wheat grain yield in conventional tillage was significantly greater than no-tillage and sweep/LASC systems. Rasmussen et al. (1997), working within

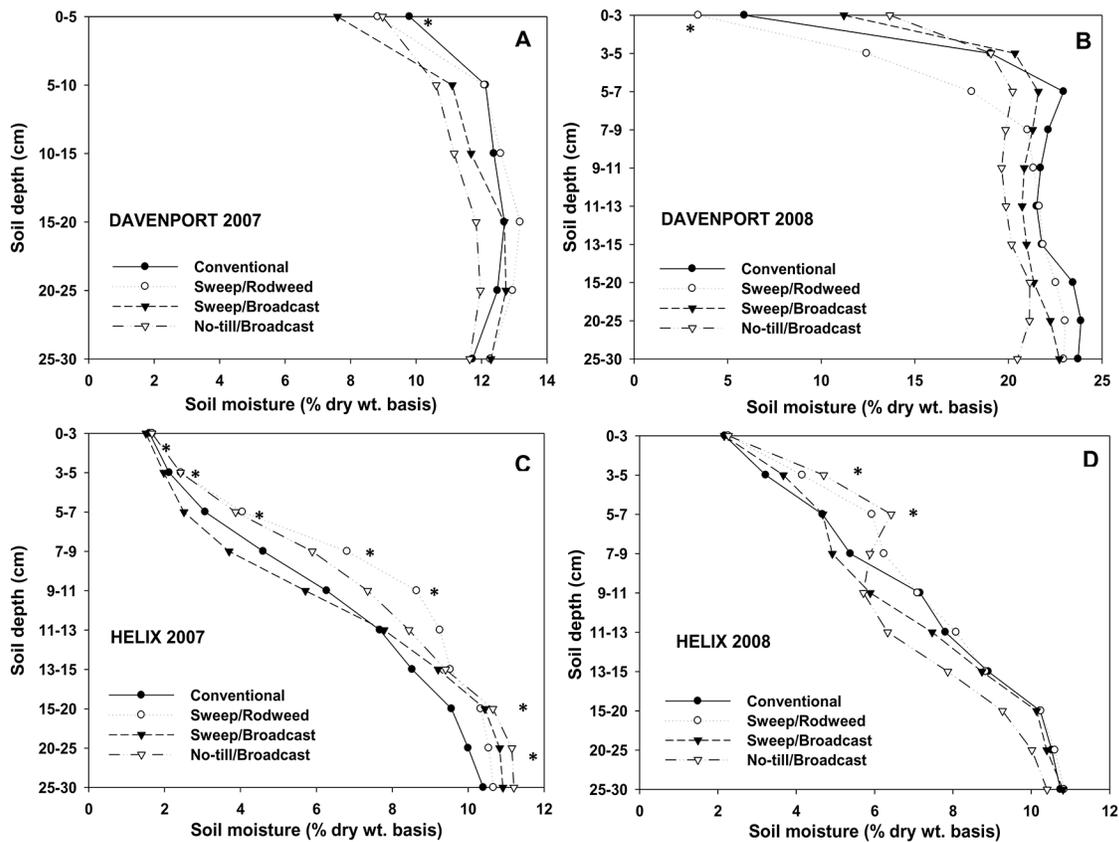


Fig. 2. A–D. Gravimetric soil moisture (% dry wt. basis) content in seed-zone soil profile at (A) Davenport, WA–2007 (B) Davenport, WA–2008 (C) Helix, OR–2007 and (D) Helix, OR–2008 fallow periods. * Represents significant difference ($P < 0.05$) between one or more treatments at respective depths. Measurements were made just before winter wheat planting on 11 and 18 September for 2007 and 2008, respectively, at Davenport, and 31 and 27 August for the same respective years at Helix.

comparative no-tillage systems, reported heavy crop residue, low soil temperatures and high pathogen activity as one reason for low winter wheat yield in no-tillage systems. Sweep/LASC and sweep/broadcast systems were assumed similar during soil sampling. Nonetheless, lower yield in sweep/LASC systems were likely due to reduced tumble pigweed control during the fallow period which reduced soil moisture available for the crop. Future investigations of soil moisture difference among sweep/LASC and sweep/broadcast systems may help in better understanding of reduced yield of sweep/LASC systems. Winter wheat yield with conventional tillage system was similar to sweep-tillage with rodweeder or broadcast spray systems that

had greater soil residue cover than conventional tillage. The higher yield in conventional, sweep/rodweed or sweep/broadcast systems compared to no-tillage and sweep/LASC systems might be due to better weed control during the fallow period or high soil temperatures at the time of seedling establishment, or both (Rasmussen et al., 1997; Camara et al., 2003).

Similarly, at Helix, sweep/rodweed produced greater wheat yield than sweep/LASC during 2007–2008 (Table 6). However, all other tillage systems had similar yields in that year. The reduced yield of sweep/LASC system was possibly due to unreliable Russian thistle control during the fallow period, which reduced soil moisture available for the cropping year. During the 2008–2009

Table 6. Wheat yield and grain protein content in different tillage treatments at Davenport, WA, and Helix, OR, during 2007–2008 and 2008–2009.

Treatment	Yield				Grain protein content			
	Davenport		Helix		Davenport		Helix	
	2007–2008	2008–2009	2007–2008	2008–2009	2007–2008	2008–2009	2007–2008	2008–2009
	kg ha ⁻¹				%			
Conventional	2800	5750	3950	3390	11.93	11.60	12.68	10.95
Sweep/rodweed	2900	5480	4000	3070	11.80	11.00	12.58	11.75
Sweep/broadcast	2470	5220	3830	3440	12.35	10.98	12.60	11.78
Sweep/LASC†	2260	5140	3380	2820	12.45	11.53	12.78	11.90
No-till/broadcast‡	2520	5070	3630	2810	12.73	11.70	12.73	11.45
No-till/LASC‡	2290	5090	3550	2650	12.43	11.30	12.70	11.53
LSD ($P \leq 0.05$)	ns	550	580	650	ns§	0.66	ns	0.52

† Abbreviations: LASC, light-activated sensor controlled sprayer.

‡ No-till treatments required reseeding (2007–2008) or were seeded at a later date (2008–2009) due to dry seed-zone moisture conditions at Helix, OR.

§ ns, not significant.

fallow–winter wheat cycle at Helix, sweep and conventional tillage systems provided similar wheat grain yield. Nevertheless, conventional and sweep/broadcast systems had greater yields than no-till/LASC system. Reduced yields of no-tillage systems were likely due to later planting of wheat in those systems.

The months of May and July were dry during 2008 at Davenport. No-tillage fallow systems tend to lose more moisture due to upward capillary flow during dry summers (Schillinger and Bolton, 1993). Moreover, the 150 cm soil profile showed less soil moisture in the deeper soil layers of no-tillage systems compared to all other systems, ultimately leaving less moisture for upward flow during dry summer period. Drought or temperature stress tends to increase protein content of grains (Gooding et al., 2003). Greater stress to wheat plants, because of drought stress, possibly increased protein content in no-tillage systems compared to sweep-tillage systems during 2008–2009. Similarly, protein content was similar among all systems at Helix during 2007–2008, but drought stress increased protein content in the sweep and no-tillage systems compared to the conventional tillage system (Table 6). Stress increased protein content in no-tillage systems, but the increase was not sufficient to cover yield loss.

CONCLUSIONS

Tillage systems affected weed density and species composition during the fallow period. Russian thistle and tumble pigweed densities were greater in sweep-tillage systems compared to conventional and no-tillage fallow. Prickly lettuce density was greater in no-tillage systems compared to other systems. These observations may be helpful in anticipating future weed problems in these different fallow systems, and allow for improved weed management planning. Soil moisture content at winter wheat seeding did not vary among tillage systems. Soil surface residue cover was greater in all reduced tillage systems compared to conventional tillage. Sweep-tillage followed by rodweeding or broadcast herbicides had similar wheat yield and grain quality as conventional tillage. However, wheat yield was comparatively less in no-tillage systems. Although, the sweep-tillage systems had similar yields as conventional tillage, sweep-tillage systems may provide a more sustainable and environmentally friendly cropping system with reduced production cost, soil erosion, dust pollution, and soil moisture losses due to less tillage operations and greater surface residue cover compared to conventional tillage. The amount of herbicide used in LASC applications was from 45 to 72% less than broadcast applications with equally effective weed control in no-tillage systems. However, additional research is necessary to fully evaluate the efficacy of the LASC sprayer in the dry and dusty conditions present during summer fallow periods of the PNW. Moreover, concerns over the failure of the LASC sprayer to detect very small weeds could require a second pass when seedling growth is advanced, which may reduce potential advantage of reduced herbicide use per application. Ultimately, LASC sprayers with improved efficacy, due to greater herbicide rates and proper application timing, could prove useful for conservation tillage fallow systems of the PNW.

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