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Delayed Glyphosate Application for No-Till Fallow in the Driest Region of the Inland Pacific Northwest

Larry K. Lutcher*

Farmers typically use three applications of glyphosate to control weeds in no-till fallow. Some are now experimenting with an unconventional modification to this widely used approach. This modified approach is based on an intentional delay in the time of the first spraying. Farmers delay their first spraying because they want to rely on competition from winter annual grasses to suppress the growth of Russian thistle and eliminate the need for a third application. Optimism for this kind of weed-control program is tempered by concerns related to soil water storage. The objective of this research was to evaluate effects of delayed control of downy brome and volunteer winter wheat on the plant-available water content of, and loss of water from, no-till fallow. Treatments, applied to plots arranged in a randomized complete block design with four replications, were distinguished by the time of the initial glyphosate application**.** The initial early-season treatment was applied as soon as possible after emergence of downy brome and volunteer winter wheat. Initial mid-season and late-season treatments were applied 4 and 6 wk later, respectively. The amount of plant-available water in the soil profile ranged from 71.8 to 153.7 mm in May and 16.5 to 80.9 mm in September. Water loss was usually minimized in plots treated with the initial early-season treatment. An exception to this trend occurred at a site where the density of downy brome and volunteer winter wheat was greater than average. Abated water loss from the initial late-season treatment, at this site, may have been a consequence of reduced evaporation caused by a decrease in near-surface wind speed and deflection of solar radiation away from soil. Estimated impacts of water loss on grain yield of winter wheat, produced the year after fallow, range from 269 to 600 kg ha^{-1}.
Nomenclature: Glyphosate; downy brome, *Bromus tectorum* L.; Russian thistle, *Salsola tragus* L.; winter wheat, *Triticum aestivum* L.
Key words: Low precipitation zone, plant competition, soil water storage.

Los productores típicamente usan tres aplicaciones de glyphosate para controlar malezas en barbecho con labranza cero. Algunos están actualmente experimentando con una modificación no-convencional a esta práctica ampliamente usada. Esta modificación está basada en un atraso intencional en el momento de la primera aplicación. Los productores atrasan su primera aplicación porque ellos quieren beneficiarse de la competencia de las gramíneas anuales de invierno para suprimir el crecimiento de *Salsola tragus* y así eliminar la necesidad de una tercera aplicación. El optimismo por este tipo de control de malezas se enfrenta a las preocupaciones relacionadas al almacenaje de agua en el suelo. El objetivo de esta investigación fue evaluar los efectos del retraso en el control de *Bromus tectorum* y el trigo de invierno voluntario sobre el contenido de agua de suelo disponible para las plantas, y la pérdida de agua en barbechos bajo labranza cero. Los tratamientos fueron distinguidos por el momento de la aplicación inicial de glyphosate y fueron arreglados en un diseño de bloques completos aleatorizados con cuatro repeticiones. El tratamiento inicial temprano durante la temporada fue aplicado tan pronto fue posible después de la emergencia de *B. tectorum* y del trigo de invierno voluntario. Los tratamientos iniciales a la mitad y tarde durante la temporada de crecimiento fueron aplicados 4 y 6 semanas después, respectivamente. La cantidad de agua disponible para las plantas en el perfil del suelo varió de 71.8 a 153.7 mm en Mayo y de 16.5 a 80.9 mm en Septiembre. La pérdida de agua fue usualmente minimizada en parcelas tratadas con el tratamiento inicial temprano en la temporada. Una excepción a esta tendencia ocurrió en un sitio donde la densidad de *B. tectorum* y del trigo de invierno voluntario fue mayor al promedio. La reducción en la pérdida de agua en el tratamiento de la aplicación inicial temprano en la temporada, en este sitio, podría haber sido una consecuencia de una evaporación reducida causada por una menor velocidad del viento cerca de la superficie del suelo y un cambio en la incidencia solar sobre el suelo. Los impactos de la pérdida de agua sobre el rendimiento de grano del trigo de invierno, producidos un año después del barbecho, variaron entre 260 y 600 kg ha^{-1}.

The winter wheat–summer fallow rotation is practiced on 1.56 million ha in the low-precipitation (< 300 mm) zone of the inland Pacific Northwest. Annual precipitation in the driest region (150,000 ha) of this low-precipitation zone, located

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in north-central Oregon and south-central Washington, ranges from 150 to 250 mm. Results from long-term experiments (Juergens et al. 2004; Schillinger and Young 2004; Young et al. 2015) are evidence that farmers must rely on a preceding year of either tillage fallow or no-till fallow to store moisture that can be used to grow a profitable crop the next year. Those who practice no-till fallow typically rely on multiple (usually three) applications of glyphosate to control weeds (Dilpreet et al. 2011; Ireland 2003; Jemmett et al. 2008). The first application in March or April is used to control winter annual grasses. The second application, usually applied in May or June, kills broadleaf species including Russian thistle—a common summer annual in fallow-based systems (Papendick 1998; Schillinger 2007; Schillinger and Young 2000, 2004; Young et al. 1995). The third application is used to treat subsequent flushes of Russian thistle. This third treatment occurs in July and is usually applied by fixed-wing aircraft, because on-the-ground spraying creates dust—a situation that leads to unacceptable weed control in the wheel-tracks of tractors or self-propelled sprayers.

Farmers are experimenting with an alternative and potentially less expensive strategy. This unconventional approach is based on an intentional delay in the time of the first spraying. Those who use this method rely on competition (Didon et al. 2014; Young 1986), provided by a more prolific population of winter annual grasses, to suppress or postpone germination, emergence, and POST growth of Russian thistle. The overall effect is a decreased window of opportunity for establishment of this troublesome weed and, in some cases, elimination of the need for a third herbicide application.

Optimism for this alternative weed-control strategy is tempered by concerns related to soil water storage (Greb and Zimdahl 1980; Nesse and Ball 1994; Wicks and Smika 1973). Soil water storage can be reduced significantly when weeds are not controlled in a timely fashion. The magnitude and impact of this reduction has been evaluated in the past, but these efforts focused either on dissimilar climatic zones (Smika and Wicks 1968), broadleaf weed species (Dwyer and Yohannis 1972; Wiese 1960), tillage-based systems (Fenster and Wicks 1982), green fallow (Nielsen and Vigil 2005), or an optimum or near-optimum application time (Hoefer et al. 1981). The objective of this research was to evaluate the plant-available water content of, and loss of water from, no-till fallow treated with timely and delayed applications of glyphosate for the control of downy brome and volunteer winter wheat (volunteer).

Materials and Methods

Overview. Field research was conducted at two (separate) sites in Morrow County, Oregon during 2009 and 2010. Experimental sites, hereafter referred to by soil type, were located in fields of no-till fallow. The soil in one of the fields (45.51°N, 119.59°W) is a 90-cm deep Mikkalo silt loam (Calcidic Haploxeroll). The soil in the other field (45.56°N, 119.62°W) is a 90-cm deep Willis silt loam (Orthidic Durixeroll). First- and second-year experiments on each soil were positioned on opposite sides of a county road—separated by an approximate distance of 100 m. The Mikkalo and Willis soils occupy flat landscape positions and are 400 to 425 m above sea level. They are characterized by low organic carbon (7 to 9 g kg^{-1}), pH values from 6.9 to 7.3, and a CEC of 12 to 14 $cmol_c$ kg^{-1}. Annual precipitation, most of which occurs during winter, ranges from 150 to 250 mm. Summers are dry, hot, and windy. Growing conditions are representative of 150,000 ha in north-central Oregon and south-central Washington—the driest wheat-producing region of the inland Pacific Northwest.

Weed Species. Downy brome, volunteer, and Russian thistle were predominate weed species on the Mikkalo and Willis soils. The population of downy brome and volunteer was estimated in March, before application of the initial early-season treatment, by counting the number of plants in a 30-cm^2 area at eight representative locations of each field experiment. Scaled-up population estimates are reported as the number of plants m^{-2}.

The overall density of Russian thistle plants, which was typical of conditions encountered in no-till fallow of the region, was moderately severe. Plants first emerged in March or April and were distributed more or less uniformly (approximately 3 plants m^{-2}) across the area within experimental boundaries. May and June flushes were small, irregularly shaped patches in each plot.

Table 1. Application dates for early-season, mid-season, and late-season glyphosate treatments.

Treatment	Date of first glyphosate application	Date of second glyphosate application	Date of third glyphosate application[a]
2009 experiments			
Early-season	April 3, 2009	June 8, 2009	July 19, 2009
Mid-season	April 30, 2009	June 29, 2009	July 26, 2009
Late-season	May 13, 2009	July 6, 2009	July 31, 2009
2010 experiments			
Early-season	March 12, 2010	May 12, 2010	July 1, 2010
Mid-season	April 9, 2010	June 5, 2010	July 7, 2010
Late-season	April 24, 2010	June 26, 2010	July 15, 2010

[a] Third glyphosate application not required on the 2009 Mikkalo soil.

Herbicide Treatments. Treatments (Tables 1 and 2), applied to plots (4 by 55 m) arranged in a randomized complete block design with four replications, were distinguished by the time of the initial glyphosate (Gly Star® Plus, Albaugh, Inc.) application. The initial early-season treatment was applied as soon as possible after emergence of downy brome and volunteer. The initial mid-season treatment was applied when there were one or two nodes on the main stem of downy brome plants and volunteer was transitioning from vegetative to reproductive growth (onset of jointing). The initial late-season treatment was applied to downy brome with emerging panicles (just before seed set) and before the accumulation of 1,000 growing degree days (Ball et al. 2004); volunteer was jointed with one or two nodes above the soil surface. Subsequent glyphosate applications, for each of the three treatments, were made on an as-needed basis for the control of Russian thistle. Treatments were applied to plots using a 4-m-wide boom sprayer (Markel Manufacturing, Heppner, OR) mounted on an all-terrain vehicle equipped with a digital speedometer and hand-controlled throttle. Glyphosate was applied (525 to 1,365 g ae ha^{-1}; Table 2) with spray-grade ammonium sulfate (20 g L^{-1}) and nonionic surfactant (2.5 g L^{-1}) at a pressure of 240 kPa through 8002 nozzles (TeeJet®, Springfield, IL) on 50-cm spacing. Application speed was 7 km h^{-1} and the total spray volume was 115 L ha^{-1}.

Table 2. Application rates for early-season, mid-season, and late-season glyphosate treatments.

Treatment	First glyphosate application rate	Second glyphosate application rate	Third glyphosate application rate
	g ae ha^{-1}		
Early-season	525	850	1,250
Mid-season	630	940	1,310
Late-season	740	1,050	1,365[a]

[a] Third glyphosate application not required on the 2009 Mikkalo soil.

Soil Sampling and Analysis. Soil sampling was conducted in the spring of the fallow year and again in late summer. Spring sampling occurred in May (14 to 15 d after the initial late-season treatment)—when downy brome and volunteer plants in all plots were desiccated. Late-summer sampling took place during the first week of September. A 120-cm-long, 7-cm-diam AMS auger (Ben Meadows Co., Janesville, WI) was used to remove samples from the 0- to 15-, 15- to 30-, 30- to 60-, and 60- to 90-cm depths near the center of three randomly selected 3- by 4-m areas within the boundaries of each plot. Soil from designated sampling areas was composited according to depth and mixed, by hand, in an 18-L bucket. A portion of each composited sample was placed into a 125-cm^3 soil moisture can. Wet weights were determined at a nearby farm shop using a calibrated electronic balance (Model SC2020; Ohaus Corp.). Dry weights were determined 24 h after samples were placed in a 105 C convection oven (Model GC, Quincy Lab Inc.).

Soil Water. Wet and dry weights were used to calculate the gravimetric water content (Gardner 1986) of soil samples. The volumetric water content of soil was calculated from gravimetric data and previously evaluated bulk density values (data not shown). The amount of water (mm) in the soil profile was determined by summing the product of volumetric water content and depth for each sampling interval. Water loss from each plot was determined by calculating the difference in the

Table 3. Monthly precipitation at 2009 and 2010 field experiments on Mikkalo and Willis soils.

	Precipitation			
	2009 experiments		2010 experiments	
Month	Mikkalo soil	Willis soil	Mikkalo soil	Willis soil
	mm			
September	0.0	0.3	2.0	1.3
October	10.4	10.2	26.4	16.5
November	10.7	2.8	22.1	9.9
December	25.9	25.4	31.0	10.9
January	26.9	24.9	48.0	54.9
February	20.3	21.8	17.0	17.8
March	26.9	38.6	24.6	18.5
April	16.5	17.3	14.2	17.8
May	25.9	25.7	69.9	32.3
June	21.1	19.8	49.5	57.7
July	3.3	0.3	2.5	3.8
August	8.6	3.0	1.8	4.3
Total	196.5	190.1	309.0	245.7

amount of water in samples collected during May and September. Reported amounts of soil water are considered to be plant available. Plant-available water was determined by subtracting unavailable soil water content values from the total amount of water in soil. Unavailable soil water content values are averages obtained from 5 yr of postharvest, before-rainfall sampling of the Mikkalo and Willis soils.

Supplemental Weed Control. Russian thistle plants were removed, by hand, from designated (3 by 4 m) sampling areas within 36 h of emergence. Supplemental weed control of Russian thistle, and an occasional prickly lettuce (*Lactuca serriola* L.) or tumble mustard (*Sisymbrium altissimum* L.), was used to eliminate confounding effects of broadleaf weed species on the plant-available water content of, and loss of water from, no-till fallow treated with timely and delayed applications of glyphosate for the control of downy brome and volunteer.

Statistics. The Statistix 8 program (Analytical Software; Tallahassee, FL) was used to interpret normally distributed data. The ANOVA/analysis of covariance option was used for an overall, mixed-model analysis of fixed (treatments) and random effects (soils and years). Data from individual sites were analyzed with the model for a randomized complete block design. Treatment means were compared using Tukey's honestly significant difference ($\alpha = 0.05$) test (LeBlanc 2004).

Results and Discussion

The overall analysis of plant-available soil water and soil water loss revealed significant two-way (year by treatment and soil by treatment) and three-way (year by soil by treatment) interactions. Interactions are probably the result of year-to-year variation in the quantity of precipitation (Table 3) and an unusually dense population of downy brome and volunteer on the 2009 Mikkalo soil (Table 4). Results described in subsequent paragraphs of this publication were generated from the statistical analysis of data from individual sites (Tables 5 and 6).

Amount of Plant-Available Water in Soil. The amount of plant-available water in the soil profile ranged from 71.8 to 153.7 mm in May (Table 7) and 16.5 to 80.9 mm in September (Table 8). Treatment effects were especially evident on the heavily infested Mikkalo soil in May of 2009 and on the Willis soil in September of the same year. Treatment-induced differences for the Mikkalo soil appear to be mostly a function of changes that occurred at 15- to 30- and 30- to 60-cm depths. Effects in the Willis soil may be an outcome of relatively large changes that occurred in 30- to 60- and 60- to 90-cm layers of soil. These results from

Table 4. Descriptive statistics for winter annual grass populations on Mikkalo and Willis soils in 2009 and 2010.[a]

	Estimated downy brome population				Estimated volunteer winter wheat population			
	2009 experiments		2010 experiments		2009 experiments		2010 experiments	
Statistic	Mikkalo soil	Willis soil	Mikkalo soil	Willis soil	Mikkalo soil	Willis soil	Mikkalo soil	Willis soil
	Plants m^{-2}				Plants m^{-2}			
N	8	8	8	8	8	8	8	8
Min.	54	0	0	0	32	0	0	11
Max.	183	86	97	32	151	118	75	43
Mean	112	26	30	5	67	36	33	27
Std. Dev.	47	30	33	11	45	47	25	14

[a] Populations of downy brome and volunteer winter wheat were estimated in March, before application of the initial, early-season treatment.

2009 are evidence that delayed control of transpiring weeds is of special concern and evaporation, after downy brome and volunteer are killed, can be substantial. There was no disadvantage to the mid-season treatment in 2010. The 2010 late-season treatment reduced the amount of water in the soil profile, compared with the early-season treatment, by an average of 14.5 mm in May and 28.2 mm in September.

Plant-Available Water Loss from the 2009 Mikkalo Soil. Plant-available water loss (Table 9) from the 2009 Mikkalo soil was minimized in plots treated with the late-season glyphosate application. This contradictory outcome may be a consequence of factors related to the density of downy brome and volunteer. Downy brome and volunteer plants, although desiccated, were vertically oriented and 20 to 36 cm tall. This "standing" residue may have reduced evaporation by minimizing wind speed

Table 5. ANOVA for plant-available water in May, plant-available water in September, and plant-available water loss, by depth, for 2009 Mikkalo and Willis soils.[a]

		2009 mean square values, by soil type					
		Plant-available water in May		Plant-available water in September		Plant-available water loss (May–September)	
Source (by depth)	df	Mikkalo soil	Willis soil	Mikkalo soil	Willis soil	Mikkalo soil	Willis soil
0–15 cm							
Trt	2	199.14	1.04	6.52	15.38	150.01	10.21
Rep	3	4.89	0.65	0.48	0.98	8.36	2.04
Error	6	3.24	0.14	0.50	0.21	3.81	0.52
15–30 cm							
Trt	2	108.89	6.64	11.32	28.20	53.11	7.23
Rep	3	5.71	0.09	1.35	1.82	12.55	2.32
Error	6	0.58	0.24	1.30	0.83	1.76	1.15
30–60 cm							
Trt	2	153.58	5.24	95.11	159.94	9.55	109.27
Rep	3	8.52	1.44	0.13	2.17	10.15	6.49
Error	6	1.08	5.16	1.70	2.30	2.76	9.03
60–90 cm							
Trt	2	28.57	6.49	51.54	289.31	22.41	295.33
Rep	3	13.81	14.48	2.00	6.07	5.87	14.34
Error	6	1.09	1.44	3.09	0.59	2.50	1.04
Soil profile							
Trt	2	1,560.97	40.68	517.51	1,476.90	290.40	1,050.07
Rep	3	34.55	12.79	9.91	17.85	58.08	47.84
Error	6	8.20	7.88	7.94	4.94	5.46	5.16

[a] Abbreviations: Trt, treatment; Rep, replication; df, degrees of freedom.

Table 6. ANOVA for plant-available water in May, plant-available water in September, and plant-available water loss, by depth, for 2010 Mikkalo and Willis soils.[a]

		2010 mean square values, by soil type					
		Plant-available water in May		Plant-available water in September		Plant-available water loss (May–September)	
Source (by depth)	df	Mikkalo soil	Willis soil	Mikkalo soil	Willis soil	Mikkalo soil	Willis soil
0–15 cm							
Trt	2	0.43	0.71	30.33	28.02	24.76	22.69
Rep	3	4.33	1.96	2.03	4.74	4.02	1.96
Error	6	5.50	1.37	1.68	0.39	11.34	0.72
15–30 cm							
Trt	2	1.46	5.60	19.14	23.90	18.32	6.54
Rep	3	2.88	3.50	3.47	8.01	2.02	11.05
Error	6	0.41	0.50	1.26	0.58	1.96	1.39
30–60 cm							
Trt	2	19.80	11.32	56.93	120.24	10.24	58.82
Rep	3	4.15	4.52	7.39	16.35	7.67	25.20
Error	6	2.61	6.75	3.02	6.47	6.72	4.42
60–90 cm							
Trt	2	87.50	49.17	106.29	78.04	0.95	16.74
Rep	3	7.13	6.24	25.90	0.77	18.19	4.68
Error	6	5.18	12.80	4.49	3.49	8.87	21.87
Soil profile							
Trt	2	214.69	178.65	767.53	895.99	173.20	326.18
Rep	3	25.34	32.74	118.19	85.76	49.72	112.69
Error	6	28.35	34.27	30.80	22.41	74.17	31.98

[a] Abbreviations: Trt, treatment; Rep, replication; df, degrees of freedom.

near the soil surface and redirecting solar radiation away from soil (Lemon 1956; Wuest and Schillinger 2011). Reduced water loss from the late-season treatment was not a remedy for the effects of delayed control on measured amounts of plant-available water in September.

Plant-Available Water Loss from the 2009 Willis Soil and Both 2010 Soils. Plant-available water loss from the 2009 Willis soil and both 2010 soils was minimized in plots treated with the early-season glyphosate application (Table 9). The effect was most pronounced on the Willis soil in 2009. At this site, a 27-d (mid-season treatment) and 40-d (late-season treatment) delay in the time of the initial glyphosate application increased soil profile water loss by 23.6 and 29.2 mm, respectively. Differences in the top 30 cm of the soil profile were not large enough to be practically important. Evaporative water loss is a common occurrence in the top 30 cm of no-till fallow (Hammel et al. 1981; Lindstrom et

Table 7. Means and mean separation test results for plant-available water in Mikkalo and Willis soils during May of 2009 and 2010.[a]

	Plant-available water in May 2009								Plant-available water in May 2010							
	Mikkalo soil				Willis soil				Mikkalo soil				Willis soil			
Soil depth (cm)	Early	Mid	Late	HSD	Early	Mid	Late	HSD	Early	Mid	Late	HSD	Early	Mid	Late	HSD
	mm								mm							
0–15	26.5	23.5	13.0	4.0	13.8	13.2	12.8	0.9	35.6	35.4	34.9	NS	14.3	13.6	13.5	NS
15–30	20.8	15.6	10.4	1.7	12.1	10.1	9.8	1.1	25.3	24.8	24.1	NS	13.7	12.7	11.3	1.5
30–60	36.0	27.4	24.0	2.3	28.6	27.3	26.3	NS	47.6	45.5	43.2	3.5	30.2	28.6	26.8	NS
60–90	29.6	26.1	24.4	2.3	31.6	31.1	29.3	NS	45.2	42.0	36.0	4.9	31.9	27.2	25.0	NS
Soil profile	112.9	92.6	71.8	6.3	86.1	81.7	78.2	6.1	153.7	147.7	138.2	11.2	90.1	82.1	76.6	12.7

[a] Abbreviations: Early, mid, and late are early-, mid-, and late-season treatments, respectively; HSD, Tukey's honestly significant difference test ($\alpha \leq 0.05$).

Table 8. Means and mean separation test results for plant-available water in Mikkalo and Willis soils during September of 2009 and 2010.[a]

Soil depth (cm)	Plant-available water in September 2009								Plant-available water in September 2010							
	Mikkalo soil				Willis soil				Mikkalo soil				Willis soil			
	Early	Mid	Late	HSD	Early	Mid	Late	HSD	Early	Mid	Late	HSD	Early	Mid	Late	HSD
	mm								mm							
0–15	7.1	5.1	4.7	1.6	4.0	1.1	0.3	1.0	11.4	9.2	6.0	2.9	8.0	6.8	2.9	1.4
15–30	10.3	7.8	7.1	2.5	6.1	1.7	1.3	2.0	12.2	10.7	7.9	2.4	8.0	6.7	3.2	1.7
30–60	24.1	18.4	14.4	2.9	19.3	10.0	7.3	3.3	26.9	24.4	19.5	3.8	23.2	19.6	12.4	5.6
60–90	22.0	17.7	14.9	3.9	24.2	12.8	7.6	1.7	30.4	26.8	20.3	4.6	22.5	20.2	14.0	4.1
Soil profile	63.5	49.0	41.1	6.2	53.6	25.6	16.5	4.9	80.9	71.1	53.7	12.1	61.7	53.3	32.5	10.3

[a] Abbreviations: Early, mid, and late are early-, mid-, and late-season treatments, respectively; HSD, Tukey's honestly significant difference test ($\alpha \leq 0.05$).

al. 1974; Lutcher et al. 2010; Oveson and Appleby 1971; Schillinger and Bolton 1993), so it seems reasonable to hypothesize that losses caused by uncontrolled (transpiring) plants may only result in losses that will eventually occur anyway.

Disadvantages associated with delayed treatments were less pronounced in 2010. This is probably the result of abundant May and June rainfall (Table 3). The difference in soil profile water loss between the early-season treatment and the late-season treatment (applied 43 d later) was 15.7 mm on the Willis soil. This water loss value is relatively small in contrast to that measured in samples collected during the previous year.

Estimated Impact on Grain Yield. Soil water loss from no-till fallow will reduce the yield potential of a subsequent winter wheat crop. The estimated yield reduction associated with the mid-season treatment on the 2009 Willis soil is 269 to 377 kg ha^{-1}. Corresponding values for the late-season treatment are 431 to 600 kg ha^{-1}. The yield loss associated with the 2010 late-season treatment (Willis soil) is 290 kg ha^{-1}. Estimated impacts of water loss on yield are based on statistical relationships developed from extensive work (Leggett 1959; Schillinger et al. 2008) conducted in fallow-based cropping systems.

This research supports the intuitively logical assumption that maximum soil water storage in no-till fallow can be achieved when downy brome and volunteer are controlled as soon as possible after emergence. Results from early-season and mid-season treatments in 2010 indicate that a 4-wk delay in the time of the initial glyphosate application might be an acceptable management option in a year of abundant spring rainfall. Late-season treatments increased soil profile water loss at two of the four field experiments used for this research. Conflicting results were obtained from the experi-

Table 9. Means and mean separation test results for plant-available water loss in Mikkalo and Willis soils during 2009 and 2010.[a]

Soil depth (cm)	Plant-available water loss in 2009								Plant-available water loss in 2010							
	Mikkalo soil				Willis soil				Mikkalo soil				Willis soil			
	Early	Mid	Late	HSD	Early	Mid	Late	HSD	Early	Mid	Late	HSD	Early	Mid	Late	HSD
	mm								mm							
0–15	19.4	18.4	8.3	4.3	9.8	12.1	12.5	1.6	24.2	26.2	28.9	NS	6.3	6.8	10.6	1.9
15–30	10.5	7.8	3.3	2.9	6.0	8.4	8.5	2.4	13.1	14.1	16.2	3.1	5.7	6.0	8.1	NS
30–60	11.9	9.0	9.6	3.7	9.3	17.3	19.0	6.6	20.7	21.1	23.7	NS	7.0	9.0	14.4	4.6
60–90	7.6	8.4	9.5	3.4	7.4	18.3	21.7	2.3	14.8	15.2	15.7	NS	9.4	7.0	11.0	NS
Soil profile	49.4	43.6	30.7	5.1	32.5	56.1	61.7	5.0	72.8	76.6	84.5	NS	28.4	28.8	44.1	12.3

[a] Abbreviations: Early, Mid, and Late are early-, mid-, and late-season treatments, respectively; HSD, Tukey's honestly significant difference test ($\alpha \leq 0.05$).

ment on the 2009 Mikkalo soil. Minimum water loss from the 2009 Mikkalo soil, which was plagued by an excessively dense population of downy brome and a greater-than-average quantity of volunteer, was measured in plots where the initial glyphosate treatment was applied 40 d after the initial early-season application. Effects of the late-season treatment, at this site, may be attributed to reduced evaporation of water from soil. Estimated grain yield reductions associated with delayed control (before seed-set) of downy brome and volunteer, during years of normal ($<$ 250 mm) precipitation, range from 269 to 600 kg ha^{-1}.

The Russian thistle population on the 2009 Mikkalo soil was affected by competition from desiccated downy brome and volunteer in plots treated with the initial, late-season glyphosate application. Competition in these plots suppressed the germination and emergence of Russian thistle seedlings during June and eliminated the need for a third spraying. Infrequent elimination of the third glyphosate application will not circumvent inevitable problems associated with herbicide resistance in weed species exposed to long-term selection pressure, and it is unlikely that "up-front" cost savings would offset the economic impact of water loss on the yield of winter wheat produced the following year. Potential disease and nematode problems, exacerbated by a prolonged green bridge, could add to the cost of a delayed weed-control management plan (Cook and Veseth 1991; Smiley 2009; Smiley et al. 2005).

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