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Integrated Weed Management Systems Identified for Jointed Goatgrass (*Aegilops cylindrica*) in the Pacific Northwest

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Jointed goatgrass is an invasive winter annual grass weed that is a particular problem in the low to intermediate rainfall zones of the Pacific Northwest (PNW). For the most part, single-component research has been the focus of previous jointed goatgrass studies. In 1996, an integrated cropping systems study for the management of jointed goatgrass was initiated in Washington, Idaho, and Oregon in the traditional winter wheat (WW)–fallow (F) region of the PNW. The study evaluated eight integrated weed management (IWM) systems that included combinations of either a one-time stubble burn (B) or a no-burn (NB) treatment, a rotation of either WW–F–WW or spring wheat (SW)–F–WW, and either a standard (S) or an integrated (I) practice of planting winter wheat. This study is the first, to our knowledge, to evaluate and identify complete IWM systems for jointed goatgrass control in winter wheat. At the Idaho location, in a very low weed density, no IWM system was identified that consistently had the highest yield, reduced grain dockage, and reduced weed densities. However, successful IWM systems for jointed goatgrass management were identified as weed populations increased. At the Washington location, in a moderate population of jointed goatgrass, the best IWM system based on the above responses was the B:SW–F–WW:S system. At the Washington site, this system was better than the integrated planting system because the competitive winter wheat variety did not perform well in drought conditions during the second year of winter wheat. At the Oregon site, a location with a high weed density, the system B:SW–F–WW:I produced consistently higher grain yields, reduced grain dockage, and reduced jointed goatgrass densities. These integrated systems, if adopted by PNW growers in the wheat–fallow area, would increase farm profits by decreasing dockage, decreasing farm inputs, and reducing herbicide resistance in jointed goatgrass.
Nomenclature: Jointed goatgrass, *Aegilops cylindrica* Host AEGCY; wheat, *Triticum aestivum* L. 'Madsen', 'Stephens', 'Penawawa', 'Rod', 'Eltan', 'Alpowa'.
Key words: Crop production, integrated planting practices, crop rotation.

La *Aegilops cylindrica* Host AEGCY es un zacate invasivo anual de invierno, que representa un problema en zonas de lluvia de escasa a moderada del Pacifico Noreste (PNW). En la mayoría de los casos, el enfoque de los estudios previos acerca de *Aegilops cilíndrica*, ha sido la investigación de un solo componente. En 1996, un estudio integrado de sistemas de cultivo para el manejo de *Aegilops cylindrica*, se inició en Washington, Idaho y Oregón en la región tradicional *Triticum aestivum* L. de invierno (WW)–barbecho (F) en el PNW. El estudio evaluó ocho sistemas integrados de manejo de malezas (IWM) que incluyeron combinaciones de ya sea, una quema única de rastrojos (B) o sin quema (NB), o bien de una rotación de WW–F–WW o *Triticum aestivum* L. de primavera (SW)–F–WW y de una práctica normal (S) o una integrada (I) de siembra de *Triticum aestivum* L. de invierno. Este estudio es el primero en evaluar e identificar sistemas completos IWM para el control de *Aegilops cylindrica* en el cultivo de *Triticum aestivum* L. de invierno. En la locación Idaho, con muy baja densidad de malezas, no se identificó ningún sistema IWM que consistentemente lograrà reducir al máximo la pérdida del grano y las densidades de la maleza. Sin embargo, se identificaron sistemas IWM exitosos para el manejo de *Aegilops cilíndrica* conforme se fueron identificando las poblaciones de las malezas. En la locación Washington, con una moderada población de *Aegilops cylindrica*, el mejor sistema IWM basado en la respuesta anteriormente citada fue el sistema B:SW–F–WW:S. En Washington, este sistema fue mejor que el sistema de siembra integrado porque la variedad competitiva del *Triticum aestivum* L. de invierno no se desarrollo bien en condiciones de sequía durante el segundo año. En Oregón, una locación con una alta densidad de malezas, el sistema B:SW–F–WW:I obtuvo consistentemente mayores rendimientos de grano, redujo la pérdida del mismo y disminuyó la densidad de *Aegilops cylindrica*. Si los productores en PNW adoptaran estos sistemas integrados en la región del *Triticum aestivum* L.–barbecho, incrementarían sus ganancias al disminuir la pérdida del grano, los insumos del campo y la resistencia del *Aegilops cylindrica* al herbicida.

The term *integrated pest management* (IPM) was first introduced by Smith and van den Bosch in 1967. They described IPM as the integration of various control strategies and applications of ecological principles to control pests in agricultural systems. Numerous definitions and goals have been stated for IPM. Regardless of which ones are cited, IPM contains two elements: the integration into a management system of the knowledge of a pest's biology and ecology, and the use of numerous control methods for the particular pest or pests (Buhler 2002). Unfortunately, IPM systems have focused, and continue to focus, on important insect pests and plant diseases despite weeds being the major pest in most cropping systems.

There is, however, a component of IPM that focuses primarily on weeds, and that is integrated weed management (IWM)(Shaw 1982; Thill et al. 1991). The concept of IWM was first introduced in the mid 1970s (Buchanan 1976), and

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since then, the weed science community has embraced the concept and recognized its importance. The Weed Science Society of America has sponsored four IWM symposia at their national meetings (Elmore 1991; Miller 1982; Sanyal 2008; Van Gessel 1996) as well as a 50th Anniversary–invited article entitled "Challenges and Opportunities for Integrated Weed Management" (Buhler 2002). There has been a myriad of literature on IWM, such as research articles (Blackshaw et al. 1999; O'Donovan et al. 2007; Schrieber 1982; White et al. 2004; Young et al. 1994), a book chapter (Liebman and Gallandt 1997), and a book (Liebman et al. 2001), to mention only a few. There are numerous other books and book chapters written on IWM or weed control systems or both; however, the authors often discuss each component of IWM separately and not in combination.

In simple terms, IWM is the process of combining several single management strategies together to suppress weeds (Gill et al. 1997; Liebman and Gallandt 1997; Shaw 1982). Some of these strategies include diversified crop rotations; competitive crop varieties planted at an optimum timing, row spacing, and seeding rate; precision and proper timing of fertilizer applications; field sanitation; seedbed preparation; and chemical and preventative weed control methods. A single input should only be considered as a portion of an IWM strategy.

It is common knowledge to scientists conducting weed research in cereal grains how problematic jointed goatgrass is to winter wheat producers in the western United States. So devastating was this weed that in 1994 a National Jointed Goatgrass Research Program was initiated to provide federal funding for research on the management, biology, and ecology of this weed and for technology transfer (http://www.jointedgoatgrass.org). Since the 1970s, the vast majority of nongenetic research on jointed goatgrass has focused on single-component management strategies (Young et al. 2002). In 1996, a long-term, integrated management study for jointed goatgrass was initiated in the central Great Plains in Kansas (White et al. 2004). The hypothesis of the study was that the integration of competitive winter wheat varieties with reduced summer-fallow tillage, compared with no tillage and diversified crop rotations, would expedite control and reduce the impact of jointed goatgrass more than any of the component practices alone. This study and other long-term integrated studies for jointed goatgrass management in western regions (Klein and Hanson 2009; Whitesides et al. 2009) and states (Miller et al. 2009; Peeper 2009; Westra et al. 2009) did not evaluate systems but rather individual treatments or factors.

In contrast to these studies, the goal of the PNW study was to develop and identify a production system or systems that integrated several effective, previously studied, single-component management practices to suppress the competitive effects of jointed goatgrass against wheat (Young et al. 2002). The integrated management practices included one-time stubble burning (Young et al. 1990), rotation out of winter wheat production (Young et al. 2000), and several improved strategies for planting winter wheat. These nonclassical, cultural-control strategies for planting winter wheat included deep-banded nitrogen (N) at the time of planting (Mesbah and Miller 1999), the use of competitive wheat varieties (Ogg and Seefeldt 1999), increased crop seeding rate (Kappler et al. 2002), and large seed. The objectives of this study were to identify IWM systems consisting of these inputs that reduce jointed goatgrass infestations and grain dockage and improve crop yield.

Materials and Methods

A 6-yr field study was conducted at Lewiston, ID; Lacrosse, WA; and Gooseberry, OR, from 1996 to 2001 to determine the best combination of treatments (best system) for the management of jointed goatgrass. Although rainfall varies among locations ($<$ 30 cm for Oregon, 30 to 38 cm for Washington, and $>$ 40 cm for Idaho)(Table 1), the most common crop rotation for all three locations is summer fallow (F)–winter wheat (WW). All experiments were conducted on silt loam soils; however, soil properties varied with location (Table 2). Experiments were initiated in the fall of 1996 in standing spring wheat stubble in Idaho and standing winter wheat stubble in Washington and Oregon in natural infestations of jointed goatgrass.

Experiments were designed as a randomized complete block with a split–split plot arrangement and four replications. All main, subplots, and sub-subplots were randomized the first year. Main plots were either a one-time burn (B) or no burn (NB), and subplots were lengths of time out of winter wheat production: either 1 yr with an F–WW–F–WW rotation, or 3 yr with an F–spring wheat (SW)–F–WW rotation. The sub-subplots were 3 m wide and 18 m long and consisted of the cooperating growers' standard (S) practice of planting winter wheat and an integrated (I) practice of planting winter wheat. In all, there were eight systems evaluated: two burn treatments, two rotations, and two winter wheat planting practices.

In general, the integrated planting practices for winter wheat included planting a competitive variety, increased seeding rates and seed size, fertilizing (N and sulfur [S]) at seeding, and using starter fertilizer (phosphorous [P]) with the seed. Even though the competitive varieties' seed were screened to contain 30 to 50% of the larger seed within a lot of seed, seed size was not always larger for the competitive variety compared with the standard variety. For example, the hundredweight of the standard variety of seed planted in Washington in 1997 was 4.4 g. In contrast, the hundredweight of the screened, competitive variety was 4.0 g. Wheat seed for all plantings was purchased commercially.

Winter wheat was harvested in late July or early August depending on location in 1998 and 2000, and SW was harvested August 1998 in Washington and Oregon with a 1.5-m-wide plot harvester. Yields are reported at 0% moisture and 0% foreign matter. Jointed goatgrass dockage was estimated by separating spikelets from a 100-g subsample of the harvested wheat grain and expressing jointed goatgrass weight as a percentage of the total subsample weight (Ball et al. 1999).

Jointed Goatgrass Spikelet and Plant Density. In the fall of 1996, all sub-subplots at all locations were sampled for jointed goatgrass spikelets before (baseline data; Table 3) and after

Table 1. Crop-year precipitation[a] for 5 yr for Lewiston, ID; LaCrosse, WA; and Gooseberry, OR.

Seasonal precipitation	1996–1997	1997–1998	1998–1999	1999–2000	2000–2001
	mm				
Lewiston, ID					
September to November	98	98	132	72	111
December to February	146	68	73	108	60
March to May	128	151	77	86	79
June to August	62	88	70	36	47
Total	434	405	352	302	297
LaCrosse, WA					
September to November	173	115	86	62	102
December to February	236	127	174	157	94
March to May	114	100	38	135	115
June to August	45	47	40	28	47
Total	568	389	338	382	358
Gooseberry, OR					
September to November	47	77	46	74	101
December to February	68	94	36	101	52
March to May	144	136	31	62	90
June to August	52	21	41	0	57
Total	311	328	154	237	300

[a] Crop-growing season is September 1 through August 31.

(Table 4) stubble burning. Spikelets were sampled in each plot from five, 0.25-m^2 quadrats placed randomly on the soil surface and two soil cores within each quadrat: 0 to 10 cm and 10 to 20 cm deep (1,000 cm^3 each). Residue was vacuumed from the soil surface in each quadrat. Immediately after sampling for baseline spikelet densities, wheat stubble in designated main plots was burned and spikelets were again sampled randomly from the soil surface in all sub-subplots as described previously. In the greenhouse, spikelets were removed from the residue and soil using a water-spray system described previously (Kovach et al. 1988). Seed viability was determined using tetrazolium tests that compared stained seeds sampled in our study to photographs of known germinated and ungerminated seeds (A. G. Ogg, Jr., personal communication). To determine the effect of burning, the density and seed viability of spikelets after burning were compared with the density and seed viability of spikelets from the nonburned plots.

Each fall, subsequent jointed goatgrass spikelet densities were sampled on the soil surface in fallow plots before planting winter wheat and after harvesting wheat using the same procedures described above. In general, jointed goatgrass plants were counted in the spring in four to six (depending on location) quadrats selected randomly in each plot. Quadrats were either 0.25 or 0.5 m^2 depending on plant density (larger quadrat for low population); however, the same size quadrat was used for all plots at the same location for a given year. All plant counts are expressed for an area of 1 m^2. At Idaho, in 1998 (spring wheat) and 2000 (final wheat crop), and in Washington and Oregon, in 2000 (final wheat crop), jointed goatgrass plants were counted in the spring in the growing wheat crop. All other plant counts were recorded during fallow before any tillage operation or herbicide application.

General Field Procedures. Field procedures varied slightly from location to location depending on researchers' and growers' equipment and normal field and conservation practices of the region. During the first year of fallow at Idaho (1996 to 1997) broadleaf and grass weeds were controlled with a combination of herbicide applications in the fall, spring, and summer and with two tillage operations (chisel plow with a tine-tooth harrow) in the summer. During the second year of fallow (fall 1998 to fall 1999), all plots were chemical-fallowed, as opposed to the combination of chemical and tillage fallow during the previous cycle. Winter wheat was planted (Table 5) in both the integrated and standard systems using a Haybuster drill[1] with disc openers spaced 25 cm apart. In the same one-pass operation, a season-long supply of N, P, and S (based on soil tests to achieve average wheat yields of each location) was placed below the soil surface in both the integrated and standard systems. In the spring of 1999 (Table 5), spring wheat was planted and fertilized simultaneously following an 18-mo fallow period.

After stubble burning in Washington, the area was subsoiled to break up the hard pan in all plots formed by

Table 2. Soil characteristics for Lewiston, ID, LaCrosse, WA, and Gooseberry, OR.[a]

Location	Texture	Soil type	pH	OM	Sand	Silt	Clay
				%			
Idaho	Broadax silt loam	Fine-silty, mixed superactive mesic, Calcic Argixerolls	5.4	3.6	26	57	17
Washington	Chard silt loam	Coarse-loamy, mixed mesic, Calcic Haploxerolls	6.2	1.8	34	58	8
Oregon	Valby silt loam	Fine-silty mixed mesic, Calcic Haploxerolls	5.5	1.9	36	49	15

[a] Abbreviation: OM, organic matter.

Table 3. Baseline jointed goatgrass spikelet densities and viable seed in September 1996 at Lewiston, ID; LaCrosse, WA; and Gooseberry, OR.

Site	Depth	Spikelets[a]	Seed[b]	Viable seed[c]
			no.	
Idaho	Surface	3.5	4.1	3.9
	0–10 cm	5.8	4.8	4.4
	10–20 cm	2.9	2.8	2.4
Washington	Surface	51.0	65.0	60.0
	0–10 cm	3.7	1.5	1.0
	10–20 cm	0.1	< 0.1	< 0.1
Oregon	Surface	245.0	337.0	320.0
	0–10 cm	34.0	13.0	11.0
	10–20 cm	3.0	2.0	1.0

[a] Surface spikelets collected from 0.25-m^2 area, and subsurface spikelets collected from 1,000 cm^3.

[b] Average number of seed produced by spikelets recovered.

[c] Number of viable seed as determined by tetrazolium test.

Table 4. Influence of stubble burning on the viability of jointed goatgrass seed collected on the soil surface in 1996 at Lewiston, ID; LaCrosse, WA; and Gooseberry, OR.

		Jointed goatgrass		
Site	Burn	Spikelets recovered	Seed[a]	Viable seed[b]
		no. 0.25 m^{-2}	no.	
Idaho	No	6	9	8
	Yes	2	5	2
Washington	No	50	65	60
	Yes	20	20	2
Oregon	No	275	375	360
	Yes	200	225	25

[a] Average number of seed produced by spikelets recovered.

[b] Average number of viable seed (tetrazolium test) was determined from the average number of seed produced.

previous years of tillage operations and to increase water infiltration to reduce soil erosion in the burned plots. In late March, during both fallow periods (1996 to 1997 and 1998 to 1999), glyphosate was applied to control emerged weeds before delayed primary tillage operations. Primary tillage was conducted in May using a disk at a depth of 10 cm. Secondary tillage (rod-weeding) killed weeds and sealed the dust mulch to preserve the stored soil moisture (Thorne et al. 2003). In 1997 and 1999, winter wheat plots to be planted in the standard planting practices were fertilized in May or June with a spoke-wheel injector with recommended rates of N, P, and S based on soil tests. A John Deere 9400 all-purpose drill[2] (Thorne et al. 2003) with hoe openers and an 18-cm row spacing were used to plant both the standard and integrated winter wheat plots (Table 5). A season-long supply of N, P, and S was applied at the time of planting the integrated winter wheat. Spring wheat plots were fallowed chemically from September 1996 to April 1998. Spring wheat was planted (Table 5) and fertilized simultaneously, with the same drill used to plant winter wheat.

Field operations in Oregon during the fallow years before planting winter wheat included a March application of glyphosate followed by a chisel plow/rod weeder as needed to kill weeds and seal the dust mulch. In the standard winter wheat systems, N and S (based on soil tests) were applied in June with a shank applicator in 1997 and a spoke-wheel injector in 1999. Winter wheat in the standard system was planted in 1997 using a John Deere H-Z deep-furrow drill[3] (Thorne et al. 2003) with 40-cm row spacing. The same drill used in Washington to plant wheat was used to plant winter wheat (Table 5) both years (1997 and 1999) in the integrated system and the second year in the standard system. The N, P, and S were applied below the soil surface at planting in the integrated system each year. Spring wheat was planted and fertilized in a one-pass operation using the same winter wheat drill.

For a given year and location, both the standard and integrated winter wheat were fertilized with the same amount of N and S. Broadleaf and grass weeds were controlled in the crop with appropriate herbicides, using labeled rates based on weed species present and their respective densities. Standard planting practices, except fertilizing at the time of planting, were used for spring wheat at all three locations.

Statistical Analysis. The SAS Proc Mixed procedure (SAS Institute, Inc. 1999)[4] was used to analyze the data. Because baseline jointed goatgrass natural populations varied greatly among locations, each location's sets of data were analyzed separately. Analysis of residuals was used to check the validity of the statistical assumptions of normality and homogeneity of variances. Percentages of dockage and plant densities were transformed to the natural log to normalize variances. Means were back-transformed for presentation. Hsu's multiple comparison with the best procedure (Hsu 1984) was used to select treatment combinations for a subset, such that the best treatment combination (burning status, rotation, and planting practice) is included in the subset with a 95% level of confidence. This analysis will allow growers to identify the best combination of treatments (system) for optimum production and maximum jointed goatgrass suppression.

Results and Discussion

Jointed Goatgrass Spikelet Density. Baseline spikelet densities in the fall of 1996 on the soil surface and to depths of 20 cm varied depending with location (Table 3). The natural weed infestations represented a low, moderate, and high, jointed goatgrass density for Idaho, Washington, and Oregon, respectively. Total (surface and soil cores to 20 cm deep) average spikelets ranged from < 15 in Idaho to 55 in Washington to 280 in Oregon. Viability of seed on the soil surface was $> 92\%$ at all locations (Table 3). Seed viability of spikelets beneath the soil surface was more variable and ranged from 50% to almost 100%.

Burning stubble after harvest in 1996 at the Idaho site reduced spikelet density 67% compared with preburn spikelets (Table 4). Spring wheat straw residue at this location was less than the winter wheat residue at the other locations and was not distributed uniformly (authors' personal observation). Conditions in Idaho apparently did not provide a hot, uniform burn required to substantially affect seed viability (Young et al. 1990). At Idaho, seed viability was reduced 60%. At Washington, where jointed goatgrass spikelet density was moderate and a higher, more uniform

Table 5. Crop seeding dates, rates, and cultivars for standard (S) and integrated (I) treatments at three locations from 1997 to 2000.

Treatments[a]	Date	Rate	Cultivar
		kg ha^{-1}	
1997–1998 Lewiston, ID			
WWS	September 24, 1997	110	Madsen
WWI	September 24, 1997	210	Stephens
SW	April 9, 1998	135	Penawawa
1997–1998 LaCrosse, WA			
WWS	September 10, 1997	55	Madsen–Rod mix[b]
WWI	September 10, 1997	75	Eltan
SW	April 1, 1998	90	Alpowa
1997–1998 Gooseberry, OR			
WWS	September 24, 1997	75	Stephens
WWI	September 24, 1997	115	Stephens
SW	March 11, 1998	90	Penawawa
1999–2000 Lewiston, ID			
WWS	September 29, 1999	110	Madsen
WWI	September 29,1999	210	Stephens
1999–2000 LaCrosse, WA			
WWS	September 29, 1999	70	Madsen–Rod mix
WWI	September 29, 1999	100	Eltan
1999–2000 Gooseberry, OR			
WWS	October 22, 1999	85	Stephens
WWI	October 22, 1999	120	Stephens

[a] Abbreviations: WWS, winter wheat standard; WWI, winter wheat integrated; SW, spring wheat.

[b] Madsen–Rod cultivar mix was half of each of the two cultivars by weight.

winter wheat residue was present, burning destroyed 60% of the spikelets on the soil surface and reduced seed viability 90% (Table 4). At Oregon, 30% of the spikelets were destroyed on the soil surface, and seed viability was decreased 89% (Table 4). The results in both Washington and Oregon were similar to a previous burning study (Young et al. 1990), in similar residue conditions, where spikelets destroyed ranged from 43 to 64% and seed viability was reduced 95 to 100%. In this IWM study, spikelets, seed number, and seed viability of soil-covered spikelets were not affected by burning (data not shown).

Spikelets collected on the soil surface from 1997 to 2000 were not generally affected by IWM systems (data not shown), regardless of location. No distinct pattern of a particular system's effect on surface spikelets was observed. This may be because the harvesters at each location were set to remove as many spikelets from the field as possible and to not return them to the field. This strategy has been recommended to growers to help manage jointed goatgrass. Auld et al. (1987) has stated that control of a weed in one growing season will reduce its abundance and detrimental effects on future crops and that this "carryover" effect may be dependent on either the previous year's seed production or the weed seed bank in the soil. A 2-yr study (Young et al. 2000) illustrated that the carryover effect of jointed goatgrass was spikelet production. Future analyses and discussions of the effect of IWM systems on spikelet production are in the wheat yield and quality section of this paper on how spikelets affect dockage of the harvested grain.

Jointed Goatgrass Plant Density. Because of differences in initial jointed goatgrass populations, the effect of IWM systems on weed densities will be discussed separately at each location. Jointed goatgrass plant density, as expected, varied minimally in the spring of 1997 in Washington and Oregon because stubble burning was the only systems' treatment imposed on the plots at this early stage of the study (Table 6).

Idaho Location. At Idaho, no single system consistently reduced jointed goatgrass densities (Table 6). In spring wheat and winter wheat crops in 1998 and 2000 respectively, six systems had similar weed densities within each year. It is noteworthy that in 1998 jointed goatgrass densities in spring wheat ranged from 4 to 14 plants m^{-2} and substantiates results from a concurrent study (Young et al. 2003) that jointed goatgrass can germinate, emerge, and establish itself in spring wheat. In 1999, jointed goatgrass densities were similar in all eight systems before herbicide applications in the fallow year. During the 2000 growing season, no system had a jointed goatgrass density $>$ 3 plants m^{-2}. This low density was similar to the Kansas study (White et al. 2004). In the Kansas study, crop rotation, fallow weed management methods, and wheat varieties did not affect jointed goatgrass densities when weed populations were low. Our results agree also with a study by Lyon and Baltensperger (1995) in which they found similar jointed goatgrass densities regardless of whether winter wheat production was every 2 yr or every 3 yr when weed populations were low in drought years.

Washington Location. Jointed goatgrass plants were not counted in the 1998 spring wheat crop at Washington (Table 6). Counts were recorded for 3 successive yr in the fallow period (1999), in the winter wheat crop (2000), and in the fallow period (2001) at the conclusion of the study. The B:SW–F–WW:I system was one of two systems that had the

Table 6. Best treatment combinations (systems) for reduced jointed goatgrass plant densities in the spring at three locations from 1997–2001.[a]

Treatment combinations[b]			Plant density[c]				
Burn	Rotation	Practice	1997	1998	1999	2000	2001
			no. m^{-2}				
Lewiston, ID							
B	WW–F–WW	S	—	15	1*	2	—
B	WW–F–WW	I	—	11*	4*	3	—
NB	WW–F–WW	S	—	6*	2*	< 1*	—
NB	WW–F–WW	I	—	6*	< 1**	< 1*	—
B	SW–F–WW	S	—	14	1*	< 1*	—
B	SW–F–WW	I	—	10*	1*	0**	—
NB	SW–F–WW	S	—	6*	1*	< 1*	—
NB	SW–F–WW	I	—	4**	3*	< 1*	—
LaCrosse, WA							
B	WW–F–WW	S	1*	—	56	12	43
B	WW–F–WW	I	< 1**	—	5*	6*	25
NB	WW–F–WW	S	2*	—	74	59	147
NB	WW–F–WW	I	2*	—	92	87	148
B	SW–F–WW	S	2*	—	1*	< 1*	2**
B	SW–F–WW	I	1*	—	< 1**	0**	3*
NB	SW–F–WW	S	3*	—	32	20	59
NB	SW–F–WW	I	4*	—	40	29	72
Gooseberry, OR							
B	WW–F–WW	S	160*	—	20*	77	102
B	WW–F–WW	I	95**	—	10*	40*	75*
NB	WW–F–WW	S	140*	—	53	170	173
NB	WW–F–WW	I	211*	—	24*	96	122
B	SW–F–WW	S	177*	—	11*	25*	38*
B	SW–F–WW	I	115*	—	6**	21**	23**
NB	SW–F–WW	S	140*	—	95	71	80*
NB	SW–F–WW	I	220*	—	102	90	60*

[a] ** indicates best treatment combination (system); * indicates treatments similar to best combination of treatments. Statistically significant differences are according to Hsu multiple comparisons, with the best procedure at the 5% level of significance.

[b] Abbreviations: B, burn; WW–F–WW, winter wheat–fallow–winter wheat; S, standard; I, integrated; NB, no burn; SW–F–WW, spring wheat–fallow–winter wheat.

[c] Density was recorded in the spring, either in the growing crop (1998 and 2000) or in the fallow before the spring weed control.

greatest reduction in jointed goatgrass densities during the 6-yr study (Table 6). During the fourth and fifth years of the study, this system was the optimum combination of treatments for reducing jointed goatgrass densities and was similar to the density in the best B:SW–F–WW:S system at the conclusion of the study (3 plants m^{-2} and 2 plants m^{-2}, respectively). These two systems decreased jointed goatgrass densities $> 98\%$ compared with the two NB:WW–F–WW: either S or I systems (Table 6). The NB:WW–F–WW:S system is the normal production system at the three locations. These results differ from a previous study (Yenish and Young 2004) in which the integration of wheat seed size, seeding rate, and variety height did not affect jointed goatgrass plant density. Jointed goatgrass densities in the two NB:SW–F–WW: either S or I, were intermediate between the optimum systems and the worst systems.

Oregon Location. In Oregon, three systems consistently reduced jointed goatgrass densities during the 6-yr study (Table 6). Beginning in 1999, and continuing through 2001, the optimum system for reducing jointed goatgrass densities was the B:SW–F–WW:I system. This system reduced weed populations $> 87\%$ every year compared with the worst system, NB:WW–F–WW:S, which is the normal crop production system of the region. The B:SW–F–WW:S and B:WW–F–WW:I systems had similar jointed goatgrass reductions compared with the optimum system each of the 3 yr. An interesting comparison is the B:WW–F–WW:S system with the B:WW–F–WW:I system. One characteristic that is unique to the Oregon location, compared with the other two locations, is that, by coincidence, both the grower (S planting practice) and the researcher (I planting practice) chose the same winter wheat variety, Stephens (Table 5). This variety was determined previously to be one of the most competitive PNW winter wheat varieties (Ogg and Seefeldt 1999). Thus, based on this unique circumstance, of every treatment in these two systems being identical with the exception of winter wheat planting practices, the reduction in jointed goatgrass densities (Table 6) was probably because of the planting practices. Jointed goatgrass densities were reduced 48 and 26% in 2000 and 2001, respectively, in the integrated winter wheat planting practice, compared with the standard winter wheat planting practices.

Wheat Yield and Quality. Because of differences in precipitation (Table 1) and jointed goatgrass populations (Tables 3 and 4), each location is discussed separately.

Idaho Location. During the two winter wheat growing seasons in Idaho, no system consistently produced the optimum grain

Table 7. Best treatment combinations (systems) for optimal grain yield in 1998, and grain yield and reduced jointed goatgrass dockage in 2000 at Lewiston, ID.[a]

Treatment combinations[b]			1998	2000	
Burn	Rotation	Practice[c]	Grain yield	Grain yield	JGG dockage
			kg ha^{-1}	kg ha^{-1}	%
B	WW–F–WW	S	2,755*	9,410**	0.16
B	WW–F–WW	I	2,955*	9,140*	0.57
NB	WW–F–WW	S	2,955*	8,870*	0.18
NB	WW–F–WW	I	3,425**	8,870*	0.38
B	SW–F–WW	S	—	8,735*	0.01*
B	SW–F–WW	I	—	8,465*	0.04*
NB	SW–F–WW	S	—	8,870*	0.00**
NB	SW–F–WW	I	—	8,600*	0.00**

[a] ** indicates best treatment combination (system); * indicates treatments similar to best combination of treatments. Statistically significant differences are according to Hsu multiple comparisons, with the best procedure at the 5% level of significance.

[b] Abbreviations: JGG, jointed goatgrass; B, burn; WW–F–WW, winter wheat–fallow–winter wheat; S, standard; I, integrated; NB, no burn; SW–F–WW, spring wheat–fallow–winter wheat.

[c] Integrated refers to planting practices for winter wheat only.

yield and reduced dockage (Table 7). In 1998, the best system for yield was the NB:WW–F–WW:I, whereas in 2000, the best system for yield was the B:WW–F–WW:S. However, within each year, all wheat production systems produced similar yields to the best system. Apparently, when jointed goatgrass populations are low, no specific integrated system was the best system based on yield.

Based on dockage data in 2000, however, all systems that contained spring wheat in the rotation had lower dockages than systems that contained the WW–F–WW rotations. Two systems, NB:SW–F–WW: and either S or I, had 0% dockage. These results agree with White et al. (2004) and Donald and Ogg (1991) that, by extending the time between winter wheat crops, jointed goatgrass control is improved and seed production is reduced (Wicks 1984). Perhaps, in the future, an addition of either imazamox-resistant wheat in the rotation (Ball et al. 1999) or hand-rouging scattered plants will assist further the management of low populations of jointed goatgrass. In Idaho, with a very low weed population any system with spring wheat in the rotation would be an appropriate system based on winter wheat yield and quality.

Washington Location. The first year's crops in Washington were harvested in 1998 and contained both winter wheat and spring wheat, which followed traditional fallow and chemical fallow, respectively (Table 8). Soil moisture was favorable for both varieties of winter wheat, and the seed was placed into moisture shallowly during planting in the fall of 1997. Subsequent germination and emergence of both varieties were rapid and uniform. After a one-crop growing season, the best system based on grain yield was the B:WW–F–WW:I system. The remaining three winter wheat systems had similar yields compared with the B:WW–F–WW:I system. The yields of the two nonburn, spring wheat systems were also similar to the best system, which was not the expected outcome because, normally, spring wheat yields only about two-thirds as much as a winter wheat crop (J. Burns, personal communication). Because of this yield discrepancy, most growers are reluctant to grow spring wheat. In addition to producing the highest grain yield, the B:WW–F–WW:I had the highest grain quality with 0% dockage (Table 8). Only the B:WW–F–WW:S system had similar dockage. Both nonburn winter wheat planting systems had dockage values > 1%, and unfortunately, the percentage of dockage was not measured for spring wheat.

The fall of 1999 was extremely dry; the average soil moisture line was 7.5 to 10 cm deep. The decision was made on September 29 (already 3 wk later than in 1997) to dust in the winter wheat seed at a depth of 2 cm. The decision to plant shallow wheat was based on previous research (Schillinger et al. 1998) that indicated seedlings from these varieties, when planted deep in dry conditions either died before reaching the soil surface or were unable to penetrate a light crust on the soil surface if fall rains occurred. The first significant rain after seeding occurred in early November (Table 1). From that date on, temperatures were cool, and in early December, it was observed that approximately 60% of the competitive variety Eltan had emerged compared with more than 80% emergence with the standard variety Madsen and Rod mix. Apparently, the mixture of the varieties performed better than the competitive variety in these conditions. The resulting poor stand of the competitive variety was reflected in final yield.

The best system for grain yield in 2000 was B:SW–F–WW:S (Table 8). The only other system to produce similar yields was the NB:SW–F–WW:S. The two systems that had the integrated winter wheat planting practices, including the competitive variety within each SW–F–WW rotation, yielded almost 20% less than the respective systems with the standard planting practices. All four systems that included the WW–F–WW rotation yielded less than the best system. The best grain-yielding system (B:SW–F–WW:S) also had grain quality (reduced dockage) similar to the system (B:SW–F–WW:I) with the highest quality (Table 8).

The overall best production system at the Washington site, with a moderate jointed goatgrass population, for grain yield, reduced plant densities, and high grain quality was the B:SW–F–WW:S system. The competitive variety did not perform as well the second year as it did the first year. Other competitive characteristics that need to be identified for PNW varieties include establishment in drought conditions and rapid emergence. Fast-emerging varieties are desirable (Schillinger

Table 8. Best treatment combinations (systems) for optimal grain yield and jointed goatgrass dockage in 1998 and 2000 in LaCrosse, WA.[a]

Treatment combinations[b]			1998		2000	
Burn	Rotation	Practice[c]	Grain yield	JGG dockage	Grain yield	JGG dockage
			kg ha^{-1}	%	kg ha^{-1}	%
B	WW–F–WW	S	3,495*	0.06*	4,500	1.60
B	WW–F–WW	I	4,030**	0.00**	4,165	0.32*
NB	WW–F–WW	S	3,360*	1.37	3,695	7.52
NB	WW–F–WW	I	3,560*	1.40	2,820	13.36
B	SW–F–WW	S	2,820	—	6,115**	0.06*
B	SW–F–WW	I	2,890	—	4,975	0.05**
NB	SW–F–WW	S	3,225*	—	5,915*	1.25
NB	SW–F–WW	I	3,225*	—	4,705	1.31

[a] ** indicates best treatment combination (system); * indicates treatments similar to best combination of treatments. Statistically significant differences are according to Hsu multiple comparisons with the best procedure at the 5% level of significance.

[b] Abbreviations: JGG, jointed goatgrass; B, burn; WW–F–WW, winter wheat–fallow–winter wheat; S, standard; I, integrated; NB, no burn; SW–F–WW, spring wheat–fallow–winter wheat.

[c] Integrated refers to planting practices for winter wheat only.

et al. 1998) because stand establishment is the most important single factor affecting yield in the wheat–fallow regions of the PNW (Bolton 1983). Also, crops that rapidly shade the soil surface reduce weed establishment and growth more than slower-growing crops (William and Warren 1975). Possibly, rather than, or in addition to, weed researchers' screening varieties (Ogg and Seefeldt 1999, Wicks et al. 2004), plant breeders should incorporate competitive traits into their variety selections (Wicks et al. 2004). For the most part, agronomic responses of modern wheat varieties are evaluated in weed-free conditions that do not provide information on weed–crop interactions (Seefeldt et al. 1999).

Oregon Location. As stated earlier, the Oregon location was unique and interesting from the standpoint that the same winter wheat variety was planted in both the standard and integrated planting procedures. On a short-term basis (first crop cycle), the best production system based on yield was the B:WW–F–WW:I system (Table 9). The only system comparable to the best system was the other integrated winter wheat planting system (NB:WW–F–WW:I). Compared with the two integrated winter wheat planting systems, all other systems produced at least 17% less grain. The two lowest grain-producing systems were the no burn, spring wheat systems.

The best grain quality in 1998, based on dockage, was produced in the B:SW system, where dockage was only 0.04% (Table 9). All other spring wheat systems had grain quality similar to the burn, spring wheat system, as did both the integrated winter wheat planting systems. It is important to note that even though the spring wheat systems had the lowest dockage, it was evident that jointed goatgrass germinated, emerged, produced spikelets, and contaminated the spring wheat grain. Results from a study conducted concurrently in the PNW (Young et al 2003) indicated that spring wheat was planted too early in our IWM study to completely prevent jointed goatgrass from producing spikelets. Swanton and Weise (1991) have stated that knowing the time of weed seedling emergence will assist with the discovery of weed management options that can be optimized in IWM systems. In our IWM study, delaying seeding would have optimized the effects of spring wheat on jointed goatgrass, but may have reduced spring wheat yield (Young et al 2003).

Table 9. Best combination of treatments (systems) for optimal grain yield and reduced jointed goatgrass dockage in 1998 and 2000 at Gooseberry, OR.[a]

Treatment combinations[b]			1998		2000	
Burn	Rotation	Practice[c]	Grain yield	JGG dockage	Grain yield	JGG dockage
			kg ha^{-1}	%	kg ha^{-1}	%
B	WW–F–WW	S	3,494	1.69	2,485	8.5
B	WW–F–WW	I	4,235**	0.36*	3,025*	4.1*
NB	WW–F–WW	S	3,160	3.07	2,285	19.5
NB	WW–F–WW	I	4,165*	0.48*	2,890*	6.3
B	SW–F–WW	S	3,225	0.18*	2,550	4.0*
B	SW–F–WW	I	3,160	0.04**	2,820*	1.4**
NB	SW–F–WW	S	2,690	0.32*	2,690	8.3
NB	SW–F–WW	I	2,890	0.67*	3,090**	4.3*

[a] ** indicates best treatment combination (system); * indicates treatments similar to best combination of treatments. Statistically significant differences are according to Hsu multiple comparisons with the best procedure at the 5% level of significance.

[b] Abbreviations: JGG, jointed goatgrass; B, burn; WW–F–WW, winter wheat–fallow–winter wheat; S, standard; I, integrated; NB, no burn; SW–F–WW, spring wheat–fallow–winter wheat.

[c] Integrated refers to planting practices for winter wheat only.

Winter wheat was planted in all plots in September 1999. The best IWM system, based on yield, was the NB:SW–F–WW:I system (Table 9). Similar yielding systems included all other winter wheat integrated planting systems. This result would suggest the importance of combining cultural control strategies, such as increased seed size and seeding rate and deep-banded N fertilizer, at the time of planting as well as planting competitive varieties. The highest quality grain was produced in the B:SW–F–WW:I system with only 1.4% dockage (Table 9). Two other systems that included integrated winter wheat planting practices had dockage about 4% which was not different from 1.4%. In contrast, the normal NB:WW–F–WW:S system used most commonly by growers had a dockage of 19.5%.

Over the course of the 6-yr study at the Oregon location, which was severely infested with jointed goatgrass, the overall best IWM system was the B:SW–F–WW:I system. Research from this location shows compelling results for the virtues of IWM systems in the management of jointed goatgrass. The B:SW–F–WW:I system, although similar to the best-yielding system in 2000 (Table 9), was the best system for grain quality each harvest season and the best system for reducing jointed goatgrass densities for 3 consecutive yr in the spring (Table 6). This effective system integrated a one-time stubble burn with numerous strategies for planting winter wheat and a spring wheat rotation that broke up the life cycle of jointed goatgrass by planting winter wheat every 3 yr. Over all three locations, the SW–F–WW system was the most consistent treatment for reducing jointed goatgrass dockage. In Washington (moderate weed population) and in Oregon (high weed population), integrating several techniques into one system showed that jointed goatgrass could be managed successfully without an in-crop herbicide. Anderson (1997) showed that by integrating several cultural tactics together, control of jointed goatgrass was improved. He combined a tall cultivar at an increased seeding rate with N fertilizer banded by the seed and reduced jointed goatgrass seed production 45 to 60% compared with conventional practices.

The goals of IWM are numerous and can include maximizing the profit margin (Burn et al. 1987); reducing the grower inputs, weed growth, weed seed production, and weed seed reserves in the soil (Swanton and Weise 1991); and reducing dependence on herbicides (O'Donovan et al. 2007). Using a systems approach, we have identified IWM systems that met these goals. Jointed goatgrass spikelet production and plant densities were decreased, whereas grain yield and quality were increased. At Oregon, compared with the area's normal winter wheat production system, NB:WW–F–WW:S, the B:SW–F–WW:I system reduced dockage (spikelets–weed seed–in grain) 92%, reduced plant density 86%, and increased winter wheat yield (second year) 23%. None of the systems evaluated used in-crop herbicides for jointed goatgrass; not applying herbicides will minimize possible environmental contamination (Blackshaw et al. 1999). Granted, field burning occurred in our study; however, results proved that a one-time burn in moderate to high weed populations, combined with other single-component strategies, was effective in reducing the negative effects of jointed goatgrass in the wheat–fallow regions of the PNW. Adoption of IWM systems for jointed goatgrass management has the potential to be used in the winter wheat–fallow region of the PNW, where jointed goatgrass is a problem. An important factor leading to the widespread adoption of alternative weed management strategies is having integrated the various practices together into workable systems (Blackshaw et al. 2008). The results of this study have provided growers of the wheat–fallow region of the PNW with IWM options to manage jointed goatgrass.

Sources of Materials

[1] Planting drill, Haybuster Inc., P.O. Box 1940, Jamestown, ND 58401.

[2] John Deere 9400 all-purpose drill, John Deere, One John Deere Place, Moline, IL 61265.

[3] John Deere H-Z deep-furrow drill, John Deere, One John Deere Place, Moline, IL 61265.

[4] Statistical software, Version 8.0, SAS Institute Inc., 100 SAS Campus Dr., Cary, NC 27513.

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