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Weed-species dynamics and management in no-till and reduced-till fallow cropping systems for the semi-arid agricultural region of the Pacific Northwest, USA

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Abstract

Weed management is an important consideration in implementing new cropping systems. In the semi-arid region of the Pacific Northwest, grower interest is increasing in no-till spring cropping systems because of wind erosion from traditional winter wheat *Triticum aestivum* L./dust-mulch fallow (WWF). However, no-till represents a major shift in production practices and is likely to produce new weed management challenges. A 6-year study was initiated in 1995 to develop no-till spring cropping systems and to examine associated weed management strategies for the region. Large field-size plots were delineated in two adjacent WWF fields designated west and east sites. Rotations in each site were WWF, no-till spring wheat *Triticum aestivum* L./chemical fallow (SWF), no-till continuous hard-red spring wheat (CSW), and no-till hard-red spring wheat/spring barley *Hordeum vulgare* L. (SWSB). Weed density and richness were surveyed three times each year and included late-winter, spring in-crop, and prior to crop harvest. Because of previous cropping histories, initial weed density was higher in the east than in the west plots. Weed management for east WWF was more intense than for west WWF and reduced *Bromus tectorum* L. density without a subsequent increase of other species. In contrast, weed management in west WWF was less intense and *B. tectorum* increased. No difference in weed density or richness was detected between CSW and SWSB rotations within each field site; therefore, data from these two rotations were combined and analyzed as a single continuous spring cereal (CSC) rotation. After 6 yrs, weed density was lower in east SWF and east CSC rotations at all three assessments. Weed density in the west CSC rotation was low throughout the research except for an occasional increase in volunteer cereal, but problems in chemical-fallow management increased west SWF weed density. Species richness in no-till increased in late-winter assessments after the first year as *B. tectorum* population declined and dicot species appeared. However, species richness was low at harvest assessments as herbicides controlled dicot weeds better than annual grasses. Weed populations in no-till rotations declined because of late-winter herbicide control of winter-annual weeds, in-crop herbicide control of dicot weeds, and postharvest herbicide applications to control *Salsora iberica*. The presence of wind-disseminated seed of *Lactuca serriola* L. and *Conyza canadensis* L. Cronq. in west SWF suggests these species may be future problems for long-term no-till.
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Keywords: Chemical fallow; Dust-mulch fallow; No-till spring crop; Weed management; Weed shifts; Winter wheat

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1. Introduction

No-till spring cropping is proposed as an alternative to traditional winter wheat *Triticum aestivum* L./dust-mulch fallow (WWF) on agricultural lands in the semi-arid ($<300\,\mathrm{mm\,yr^{-1}}$) Columbia Plateau region of the Pacific Northwest. In this region, a year of fallow is necessary to recharge and store soil moisture for winter wheat emergence and growth which is otherwise not possible with only a single year's precipitation (Papendick, 1998). Crop yields are highest if wheat is planted in August and September compared with seeding dates later in the fall (Donaldson et al., 2001). Evaporation of stored soil moisture is reduced by the dust mulch in the fallow system so early seeded wheat can quickly germinate and establish (Schillinger and Papendick, 1997). However, airborne particulate matter (PM)

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originating from the dry, loose-structured, unprotected dust mulch poses public health and safety issues, and decreases soil productivity (Tanaka, 1989; Hefflin et al., 1994; Saxton, 1995; Larney et al., 1998; Saxton et al., 2000; Sorensen, 2000). Most major PM emissions originate with strong winds during late-spring or early fall, but potential is greater in late-summer and early fall when the soil surface is dry and has been tilled often (Saxton, 1995). No-till cropping would help reduce PM emissions by leaving crop residues on the soil surface and eliminating tillage (Thorne et al., 2003).

No-till cropping is not widely practiced in the WWF region of the PNW because production practices have not been developed that would reduce risk of crop failure associated with such non-traditional practices. In addition, weed response to no-till spring cropping systems is unknown. Weed management strategies and associated higher expenses were the most frequent reasons growers did not adopt no-till farming in the nearby Palouse region of eastern Washington and northern Idaho (Carlson and Dillman, 1986). It is known that weed communities respond to changes in cropping systems (Clements et al., 1994; Moyer et al., 1994; Derksen et al., 2002); however, these studies have been conducted in areas receiving summer rainfall. In addition, changes in weed flora are a common response to reduced tillage (Swanton et al. 1999; Clements et al. 1996; Young et al. 1996). Previous research has indicated that annual grass and wind-disseminated weeds tend to be associated with reduced and zero-tilled systems; whereas, non-wind-disseminated dicotyledonous annual species tend to be found in plowed systems (Froud-Williams et al., 1983; Swanton et al. 1999; Tørrensen and Skuterud, 2002). However, other factors such as site, previous herbicide use, and temperature and precipitation patterns may have also influenced weed community structure (Mahn, 1984; Thomas and Dale, 1991; Andersson and Milberg, 1998; Légère and Samson, 1999).

In the Great Plains region of the United States, no-till has been included in both spring and winter wheat production systems to increase water-use efficiency and crop yield (Smika, 1990; Aase and Pikul, 1995). Weed problems that have resulted from more intensive cropping systems have included:

(1) an increase in summer-annual weeds associated with summer-annual crops, (2) increase in herbicide-resistant broad-leafed weeds, (3) greater survival of winter-annual weeds in standing no-till crop residues, and (4) perennial weeds infesting no-till systems (Derksen et al., 2002). In the traditional WWF-system, winter-annual grasses such as *Bromus tectorum* (Derksen et al., 2002) and *Aegilops cylindrica* Host (Fleming et al., 1988) are major problems in winter wheat because of similar life cycles and a lack of differential herbicide tolerance between the weeds and winter wheat. Annual broad-leafed weeds associated with WWF include *Salsola iberica* (Sennen & Pau), *Kochia scoparia* (L.) Schrad., and *Chenopodium album* L., but they are generally controlled with herbicides unless resistant biotypes are present (Derksen et al., 2002).

Both *B. tectorum* and *S. iberica* are preeminent weeds in the Pacific Northwest WWF region and are responsible for much of the tillage-induced erosion during the fallow phase of the rotation. Winter wheat yield can be reduced by 47% by *B. tectorum* (Rydrych, 1974). Dense stands of *B. tectorum* that emerged with the crop have prompted growers to destroy the crop and reseed in the fall or spring. Spring crops that are occasionally planted in the WWF region are susceptible to competition from *S. iberica*, which can reduce spring wheat yield $>50\%$ and are most competitive when the crop is stressed by moisture (Young, 1988). In addition, *S. iberica* plants growing with the crop diminish soil moisture down to 1.8-m depth, thus affecting soil moisture recharge for the next crop (Schillinger and Young, 2000). Growers either use herbicides or V-shaped sweep blades to kill *S. iberica* following harvest, which conserves soil moisture and prevents weed seed production.

Weed management implications are unknown for long-term no-till spring crops in the WWF region of the PNW. Growing spring crops should reduce *B. tectorum* and other winter-annual grass populations because these weeds can be controlled with broad-spectrum herbicides prior to seeding (Rydrych and Muzik, 1968; Rydrych, 1974). Furthermore, winter-annual grass-weed germination in spring cereals is greatly reduced (Young et al., 2003). Increase of *S. iberica* and other spring- and summer-germinating weeds and perennial weeds may pose problems for no-till production. *Conyza canadensis* and *Latuca serriola* have been increasing in no-till cropping systems in the higher-rainfall Palouse region of eastern Washington State (personal observation). The no-till crop environment differs from the tillage-based environment as accumulated surface residue moderates soil temperature and reduces moisture loss (Peterson et al., 1996; Jones and Popham, 1997). In addition, weed seeds concentrate within the surface layer, favoring species that germinate and emerge from shallow depths and within crop residues (Yenish et al., 1992; Clements et al., 1996). Because of new crop environmental conditions, weed species not currently problematic in the traditional tillage-based winter wheat fallow system may become weed management issues in no-till systems.

Producers wanting to use no-till spring cropping systems as alternatives to conventionally tilled WWF will need weed management information to help reduce the associated risk with these new systems. The objectives of this research were to (1) determine potential weed flora associated with new no-till spring cropping systems for the traditional WWF semi-arid region of the Pacific Northwest, and (2) develop weed management strategies leading to successful implementation of these no-till cropping systems.

2. Materials and methods

A large-scale cropping system study was established in the summer of 1995 on a cooperator's non-irrigated farm located in central Adams County, Washington State, USA. Long-term plots were established in two adjacent, relatively level fields with the east field in standing stubble from the 1995 winter wheat crop and the west field in fallow ready to be planted to winter wheat. Sixteen plots, each 9.1×152 m, were established in both fields. The soil was a Ritzville silt loam (coarse-silty, mixed, mesic, Calcidic Haploxeroll) with a texture of 30% sand, 62% silt, and 8% clay in both fields. Organic matter averaged 2.0% and 1.9% in east and west plots, respectively.

The four crop rotations evaluated were WWF, no-till spring wheat *T. aestivum* L./Chemical fallow (SWF), no-till continuous hard-red spring wheat (CSW), and no-till hard-red spring wheat/spring barley *Hordeum vulgare* L. (SWSB). Each rotation was included in both fields and each crop in all rotations was grown each year. With the exception of the CSW rotation, only one crop of each rotation was grown on a respective field each year and then rotated to the other field. For the initial crop year (1995–1996) the fallow phase of the WWF and SWF rotations were in the east field. The crop phase of these two rotations were on the west side with winter wheat planted in September 1995 and SW planted in spring 1996. SWSB plots were seeded in spring 1996 with SW in the west field and SB in the east field. CSW was planted in both fields. The experimental design was a randomized complete block with each rotation replicated four times at each site. All plot operations were conducted with farm-sized equipment. Precipitation was recorded on-site between 1995 and 2001 and averaged 324 mm annually on a crop year (1 September–31 August) basis. The long-term average for the study area is 305 mm y^{-1} and precipitation was above average for the first 3 years and below average for the following 3 years.

2.1. Fallow management

Following wheat harvest each year (1995, 1997, 1999), east WWF plots were lightly disked (<3 cm) to incorporate *B. tectorum* seed into the surface soil and residue layer (Table 1); west WWF plots were lightly disked only following harvest in 1998. These operations retained the integrity of the deep furrows and wheat crown roots and left the majority of the residue on the soil surface (Thorne et al., 2003). Therefore, weed seeds incorporated in the surface residue and soil could germinate and emerge during fall and winter and be killed with a glyphosate application during the following late-winter or early-spring (Table 1). Following the spring glyphosate application, WWF plots were typically undercut and fertilized with a Haybuster® non-inversion tillage implement using 0.81-m V-shaped sweeps at a depth of 13 cm. However, west WWF plots in 1997 and 1999 were tilled initially in the spring with a 10-m tandem disk harrow and attached rolling basket harrow at a depth of 10 cm to chop residue and to prevent formation of large soil clods during undercutting. Secondary tillage was performed with a set of three 3-m Calkins® rodweeders with 1.9-cm square rods

Table 1
General field operations for WWF, SWF, and CSC rotations during a 6-year cropping system study in the semi-arid region of eastern Washington, USA

	WWF	SWF	CSC
Fallow phase operations[a]			
January–March	Prefallow herbicide	Prefallow herbicide	
March–May	Primary tillage—disk or undercut and fertilize		
May–July	Rodweed tillage(s)	No-till fallow herbicide(s)	
July–September	Rodweed tillage(s) Seed winter wheat	No-till fallow herbicide(s)	
Crop phase operations[b]			
January–March	Grass-weed herbicide	Preplant herbicide Seed spring wheat	Preplant herbicide. Seed spring cereal
March–May	Broad-leafed weed herbicide	Broad-leafed weed herbicide	Broad-leafed weed herbicide
July–September	Harvest Post-harvest light disking	Harvest Postharvest herbicide	Harvest Postharvest herbicide
September–November	Grass-weed herbicide		Fall fertilize

[a] Disk operations were made with a 9-m tandem disk harrow, undercut operations were made with a 10-m Haybuster® with 81-cm V-shaped sweep blades on 66-cm spacing with liquid fertilizer nozzles spaced 30 cm underneath the blade. Rodweed operations were made with a set of three 3.7-m Calkins rodweeders using 2-cm square rods.

[b] Fertilizer was applied to spring cereals at time of seeding, and in the fall to plots going in to hard-red spring wheat the following spring.

at a depth that left 5 to 10 cm of dry loose mulch above the soil moisture line. The WWF plots were rodweeded one to three times between undercutting and seeding, depending on weed presence (Table 1).

Glyphosate was applied to SWF plots during late February or early March to control winter-annual weeds and initiate the chemical-fallow phase of the rotation (Table 1); however, in 1998, the glyphosate application was omitted in west SWF and weeds were sprayed with glyphosate plus 2,4-D in June. Following late-winter applications, glyphosate and 2,4-D were used for chemical-fallow weed control during spring and summer. Chemical-fallow herbicides were typically applied between June and September; however, a fall glyphosate application was made in 2000 to both east and west locations to control *B. tectorum* that emerged because of early-fall rains.

2.2. Crop management

Soft-white winter wheat was seeded during September, initiating each crop phase of the WWF rotation (Table 1). Seed was placed 1–2 cm into moist soil conserved by the dust mulch using a John Deere® HZ 616 deep-furrow drill with 40-cm row spacing. Lewjain cv. winter wheat was grown in 1996, 1997, and 1998, while Rely cv. winter wheat was grown in 1999, 2000, and 2001; seeding rates ranged from 34 to 50 $\mathrm{kg\,ha^{-1}}$. In 1996, winter wheat on the east plots was reseeded because plants failed to emerge after rain crusted the soil. However, before reseeding with a John Deere® 9400 hoe-opener drill with 18-cm row spacing, plots were rodweeded to control a flush of *B. tectorum*.

All spring crops were seeded with the John Deere® 9400 hoe-opener drill. The drill was equipped with 5.7-cm single-point hoe openers capable of penetrating non-tilled soil. Both dry and liquid fertilizers were applied at the time of seeding. Soft-white spring wheat Alpowa cv. was grown in the SWF rotation, while hard-red spring wheat Butte 86 cv. and Scarlet cv. and two-row spring barley Baronnesse cv. were grown in the CSW and SWSB rotations. Seeding rates for spring wheat ranged from 84 to 90 $\mathrm{kg\,ha^{-1}}$, while spring barley seeding rate ranged from 73 to 79 $\mathrm{kg\,ha^{-1}}$.

For in-crop weed control, east WWF plots had a fall/spring split application of metribuzin during the first crop year (1997) and single applications of sulfosulfuron during the second and third crop years to control *B. tectorum* (Table 1). In contrast, the west WWF plots had a single application of metribuzin in the first crop year (1996), a fall/spring split application of metribuzin in the second crop year (1998), and a single sulfosulfuron application in the third crop year (2000). In-crop applications for broad-leafed weeds in the WWF rotations were applied only to east plots. In addition, east WWF plots were sprayed with 2,4-D prior to fall seeding in 1998 to control a flush of *S. iberica*.

Prior to seeding all spring crops, plots were sprayed in early March with glyphosate to control winter-annual weeds (Table 1). Herbicides for in-crop weed control in spring crops included MCPA, bromoxynil, 2,4-D amine, tribenuron, thifensulfuron, and dicamba. Except for the west 1996 spring crops, one or more of these compounds were applied each year at labeled doses and at appropriate weed and crop stages. Herbicides were rotated to prevent weed resistance. In 1996, west spring crops had insufficient weed population to justify herbicide application. Following harvest in 1996, 1997, and 1998, *S. iberica* plants remaining in SWF and CSC plots were sprayed with paraquat herbicide to conserve remaining soil moisture and inhibit seed production (Table 1). In 1999, paraquat was applied postharvest only in the SWF plots.

All plots were harvested with a farm-size John Deere® combine equipped with an on-board scale to measure grain yield. The combine also had a chaff spreader and straw chopper for uniform distribution of crop residue and weed seeds.

2.3. Data collection

Weeds were identified and populations counted and recorded three times each year. The first assessment was in February or March (late-winter) and measured density of weeds germinating during the fall and winter period prior to spring prefallow or preplant glyphosate applications. Weed species were identified and counted within each of five 1-$\mathrm{m^2}$ sample quadrats randomly placed in each 152-m plot; however, in 1997 a 20 cm × 50 cm sample quadrate was used and counts were converted to a 1-$\mathrm{m^2}$ area. In 1996 only *B. tectorum* was counted as it was the primary species present. A second assessment each spring measured weed density during early crop growth prior to in-crop herbicide applications. These quadrats were marked so they could be resampled during the third assessment at crop maturity.

2.4. Statistical analysis

Initial tests on weed counts showed that assumptions of normality and equal variances were generally not met. A non-parametric test was used, which rank transformed data within each dependent variable and analyzed the transformed data with ANOVA using the appropriate full model (Iman et al., 1984). This analysis determined that rotations differed between east and west fields and that a significant interaction existed between the main effects year and rotation. In a separate analysis, statistical difference between CSW and SWSB rotations within each site was not detected; therefore, these rotations were combined by site and reclassified as a CSC treatment. As a result, east CSW and east SWSB became east CSC, and west CSW and west SWSB became west CSC. As suggested by Iman et al. (1984), the non-transformed data were also analyzed with ANOVA and produced similar results. For all tests, level of significance was set at $P \leqslant 0.05$.

Because of significant main-effect interactions, weed counts within each site/rotation group were analyzed separately. Within each group, e.g. west WWF, compliance with ANOVA assumptions was satisfied using a fourth-root transformation of the raw data; however, species richness data were not transformed as ANOVA assumptions were met. Data were analyzed with ANOVA using the appropriate reduced model. An additional test analyzed total weed density within each year so comparisons could be made between rotations. Data were analyzed with the general linear model procedure using SAS® software (SAS Institute Inc., 1999). Separation of means was determined with a protected Tukey's LSD test at the $P \leqslant 0.05$ significance level (Zar, 1999) using SAS® software (SAS Institute Inc., 1999). For presentation in tables, data were then back transformed.

3. Results

At the beginning of our research, east and west locations differed in their previous management and their potential for weed problems. The east field had been in a WWF rotation for more consecutive cycles than the west field, which had been planted to a spring crop 2 years prior. In addition, the east field had a greater initial weed seed bank averaging $6384\,\mathrm{m}^{-2}$ in the top 15 cm compared with $200\,\mathrm{m}^{-2}$ for the west field (data not shown). In both fields, *B. tectorum* was the primary weed species. During the first crop, west spring crops were planted into plots that had been in dust-mulch fallow the previous year; therefore, no additions to the seed bank had occurred for almost 2 years. Furthermore, weeds were controlled with herbicides prior to the 1996 spring seeding. In contrast, the east spring crops were planted into plots that had been in winter wheat the previous year and had not been tilled postharvest. These plots potentially had viable weed seeds on the soil surface produced during the previous crop cycle (Yenish et al., 1992).

3.1. *Weed management effect on tillage and herbicide operations*

Weed management decisions were prescribed individually for each rotation in each site and were based on environmental conditions and overall weed populations as well as presence of problem species. Over the course of the research, east plots accounted for more tillage operations and herbicide applications than did west plots (Table 2). The east WWF plots were shallow disked to incorporate *B. tectorum* seed into surface residue following each harvest, including postharvest 1995, while the west WWF plots were shallow disked following the 1998 harvest only.

During the dust-mulch fallow period, west WWF plots were rodweeded only once each fallow year between spring undercutting and September seeding as *S. iberica* did not emerge following the initial rodweeding. In contrast, the east WWF plots were rodweeded three times in 1996 and in 1998 primarily to control multiple emergence flushes of *S. iberica*. However, in 2000, east plots were rodweeded only once.

Herbicide applications in the three east rotations totaled 44 compared with 33 applications to the three west rotations (Table 2). In addition, east rotations received a total of $23.5\,\mathrm{kg\,ha^{-1}}$ active ingredient (a.i.) compared to $16.0\,\mathrm{kg\,ha^{-1}}$ a.i. for west rotations. Additional applications for dicot weed control in east rotations accounted for the difference in herbicide use. The east WWF rotation had three in-crop herbicide applications for dicot weed control and a fallow application just prior to fall seeding to control *S. iberica*

Table 2
Effect of rotation and site on number of tillage and herbicide operations during a 6-year cropping system study. Rotations were WWF, SWF, and CSC with each rotation included in two adjacent fields, west site and east site

	WWF		SWF		CSC[a]	
Management event	West	East	West	East	West	East
Crop years	3	3	3	3	6	6
Fallow years	3	3	3	3	0	0
Tillage operations						
Disk—postharvest	1	4				
Disk—spring	2					
Undercut	3	3				
Rodweed	3	7				
Total operations	9	14				
Herbicide applications						
Prefallow/preplant	3	3	5	6	6	6
In-crop—dicot weed		3	2	3	5	6
In-crop—grass weed	4	4				
Postharvest			2	2	2	3
Chemical fallow		1[b]	4	7		
Total applications	7	11	13	18	13	15
Total kg a.i. $\mathrm{ha^{-1}}$	2.1	4.7	7.4	11.2	6.5	7.6

[a] CSC includes two rotations in each site, CSW and SWSB. Since applications were essentially identical for CSW and SWSB at each site, values represent mean number of applications and mean total applied herbicide (a.i.).

[b] Herbicide application to control *S. iberica* prior to planting winter wheat.

Table 3
Inventory of weeds occurring during three assessment periods over the course of a 6-year cropping system study in the semi-arid region of eastern Washington, USA

Scientific name	Code[c]	Common name[c]	Assessment period (percent constancy)[a,b]		
			Late-winter	Spring in-crop	Harvest
Winter annuals					
B. tectorum L.	BROTE	Downy brome	91.4	45.7	48.6
S. altissimum L.	SSYAL	Tumble mustard	81.2	40.4	0.0
D. sophia (L.) Webb. ex Prantl	DESSO	Flixweed	67.4	23.5	5.0
L. serriola L.	LACSE	Prickly lettuce	66.7	58.1	8.6
Chorispora tenella (Pallas) DC.	COBTE	Blue mustard	0.7	3.7	0.0
Amsinckia sp.	AMS??	Fiddleneck	0.7	0.7	0.0
Volunteer crop		Wheat or barley	88.4	8.8	0.7
Summer annuals and annuals					
S. iberica Sennen & Pau	SASKR	Russian thistle	47.8	79.4	57.9
C. leptophyllum (Moq.) Nutt. ex S.Wats	CHELE	Slim-leafed goosefoot	17.4	69.1	12.1
Epilobium paniculatum Nutt. ex T. & G.	EPIPC	Panicle willowweed	4.3	12.5	0.0
C. canadensis (L.) Cronq.	ERICA	Horseweed	1.4	5.1	1.4
Polygonum aviculare L.	POLAV	Prostrate knotweed	0.7	2.2	0.0
Amaranthus sp.	AMA??	Pigweed	0.0	1.5	0.0
Sonchus asper (L.) Hill	SONAS	Spiny sowthistle	0.0	0.0	0.7
Biennials					
Tragopogon sp.	TRO??	Salsify	3.6	0.7	0.0

[a] Winter assessment occurred in February or March prior to fallow or preplant glyphosate application. Spring assessment occurred in April or May prior to in-crop herbicide applications. Harvest assessment occurred in July prior to crop harvest.

[b] Percent constancy is a measure of the ubiquity of each weed and is calculated as the percentage occurrence of each weed in all plots over all years of the study. This measure is intended only to describe species presence during the study and not the effects of management, crop rotations, or year.

[c] Code and common name based on Weed Science Society of America (WSSA) classification.

(Table 2). The east SWF had three more chemical-fallow herbicide applications and one additional in-crop dicot weed application. In CSC rotations, the east plots had one more in-crop dicot weed application and one more postharvest application (Table 2).

3.2. Occurrence of major weed species

The overall weed population consisted of 16 species and included volunteer wheat and barley (Table 3). These weeds were present at least once, in at least one plot during the study. The most common occurring weeds were *B. tectorum*, *S. iberica*, *L. serriola*, *Chenopodium leptophyilum* (Moq.) Nutt. ex S.Wats, *Sisymbrium altissimum* L., and *Descurainia sophia* (L.) Webb. ex Prantl. Of the weeds present during this research, the major focus was on the management of *B. tectorum* and *S. iberica*, because they represent major weeds in the low-rainfall region of the PNW (Rydrych and Muzik, 1968; Young, 1988). At the late-winter assessment, *B. tectorum* was present in over 90% of plots (Table 3). This is expected since *B. tectorum* is the dominant winter-annual grass weed of the region and its peak germination period is in the fall and winter (Mack and Pyke, 1983). *B. tectorum* was also present in nearly 50% of the plots at both the spring in-crop and harvest assessments (Table 3).

Presence of *S. iberica* among all plots was nearly 48% during the late-winter assessment in all plots over the course of the research (Table 3). Apparently, *S. iberica* seeds are able to germinate in relatively cool temperatures even though the species is a C4 summer annual. Mean February and March temperatures during this research were 2.9°C and 5.8°C, respectively. It was observed that *S. iberica* seedlings were killed by spring frosts, but were replaced by new recruits following frost periods. *S. iberica* was the most prevalent weed at both the in-crop and harvest assessments (Table 3), and was the primary reason for postharvest herbicide applications. In this region, a single *S. iberica* plant growing in a spring wheat crop can extract 70 l of water from the soil by crop harvest in August, and an additional 100 l by October when *S. iberica* plants succumb to killing frosts (Schillinger and Young, 2000). *S. iberica* was the primary weed problem in spring wheat and barley in this study and has kept growers from producing alternative spring crops such as dry pea (*Pisum sativum*) L., lentil (*Lens culinaris* Medik.), or spring canola (*Brassica spp.*). In addition, *S. iberica* biomass is high in moisture content at harvest which reduces harvest efficiency, increases grain moisture content, and lowers grain quality (Young, 1988).

Other weeds present at all three assessments and are of concern for crop production in the region include

L. serriola, *C. leptophyilum*, and *C. canadensis* (Table 3). *L. serriola* is a problem weed in no-till spring-crop systems in the more mesic Palouse region of eastern Washington because herbicides are not always effective (Yenish and Eaton, 2002). *C. leptophylium* is a closely related species to *C. album* L., which also represents a major weed in spring crops grown in the Palouse region. In contrast, *C. canadensis*, a common weed throughout the Pacific Northwest (Hitchcock and Cronquist, 1976), has developed herbicide resistance (Fuerst, 1985), and has been a major weed in other no-till systems (Donald et al., 2001). The winter-annual Brassicaceae weeds, *S. altissimum* and *D. sophia*, primarily occurred at the late-winter and in-crop assessment. These weeds are typically controlled with herbicides, but are potential problems for winter wheat when herbicide control or crop competition is weak (Kidder et al., 1988; Westra and D'Amato, 1989).

3.3. Crop rotation effect on weed populations

3.3.1. Winter wheat/fallow

B. tectorum densities were similar but ranged from 288 to 473 plants m^{-2} at each of the three west late-winter assessments in fallow (Table 4). These populations were controlled with herbicides and tillage during fallow operations; however, assessment counts reflect an adequate seed-bank for continued infestation (Rydrych, 1974). During the spring in-crop and harvest assessments, *B. tectorum* population increased stepwise during each of the three crop years (Table 4), indicating a trend of ongoing persistence and seed production during the crop growing season. In all three assessments, *B. tectorum* dominated the total weed density and may have out-competed other weed species.

In contrast, the east WWF *B. tectorum* population declined dramatically after the first year in all three assessments (Table 4). Late-winter *B. tectorum* population in fallow decreased from a high of 601 plants m^{-2} in 1996 to 8 plants m^{-2} in 2000, and *B. tectorum* was not present at the in-crop and harvest assessments by the third crop. During 1997, a rain immediately after seeding crusted the soil and prevented crop emergence, but stimulated a flush of *B. tectorum*. The plots were subsequently rodweeded to kill the *B. tectorum* and break the crust. *B. tectorum* that germinated after reseeding emerged well after the crop had emerged and was controlled with metribuzin before winter.

Table 4
Weed density and species richness in traditional WWF at two adjacent field sites, west and east in a 6-year cropping system study[a]

	Major weed species (weed density m^{-2})[b]							Total density	Species richness[c]
Year	BROTE	SASKR	LACSE	CHELE	DESSO	SSYAL	Vol.		
West field site									
Late-winter prefallow assessment									
1997	473 a	0 a	0 a	0 a	0 b	4 a	67 a	549 a	2.3 a
1999	288 a	0 a	0 a	T a	T a	3 a	24 b	317 a	2.6 a
2001	381 a	0 a	0 a	0 a	0 b	4 a	0 c	385 a	1.6 b
Spring in-crop assessment									
1996	14 c	—	—	—	—	—	—	—	—
1998	151 b	0 a	T b	0 a	2 a	T a	0 a	155 b	2.9 b
2000	358 a	T a	3 a	T a	3 a	1 a	0 a	368 a	4.2 a
Harvest assessment									
1996	13 c	T a	0 a	0 a	T a	0 a	0 a	13 c	0.8 a
1998	38 b	T a	0 a	0 a	0 b	0 a	0 a	39 b	1.1 a
2000	142 a	T a	0 a	0 a	0 b	0 a	0 a	143 a	1.1 a
East field site									
Late-winter prefallow assessment									
1996	601 a	—	—	—	—	—	—	—	—
1998	26 b	1 a	2 a	7 a	1 a	T a	T a	44 a	3.1 a
2000	8 b	T a	T a	0 b	T a	T a	18 a	32 a	3.1 a
Spring in-crop assessment									
1997	130 a	3 a	0 b	T b	T a	0 b	0 b	137 a	2.2 b
1999	1 b	T a	T a	20 a	T a	T a	4 a	31 b	3.9 a
2001	0 b	2 a	T b	20 a	T a	T ab	T b	24 b	2.8 ab
Harvest assessment									
1997	49 a	T a	0 a	0 a	0 a	0 a	0 a	51 a	1.5 a
1999	10 b	T a	0 a	T a	0 a	0 a	0 a	12 b	1.4 a
2001	T c	T a	0 a	0 a	0 a	0 a	0 a	T c	0.4 b

[a] Means in each column within assessment and site followed by the same letter are not significantly different ($P \leqslant 0.05$).

[b] For abbreviations see Table 3.

[c] Species richness is the mean number of species occurring each year.

At the in-crop assessment, *B. tectorum* density was 130 plants m^{-2} but declined to 49 plants m^{-2} by harvest because of crop competition and a second application of metribuzin (Table 4). Furthermore, east WWF plots were lightly disked following each crop harvest to incorporate *B. tectorum* seed into the soil surface and promote germination.

With the decline of *B. tectorum* in east WWF, a slight shift in weed composition was detected. At both the 1999 and 2001 in-crop assessments *C. leptophyllum* was the most prevalent weed (Table 4). Species richness in the east in-crop assessments was greater in 1999 as further evidence of a possible weed shift in response to *B. tectorum* decline (Table 4). However, these trends were not present at the harvest assessment as herbicides effectively controlled *C. leptophyllum* and the other dicot weeds, leaving *B. tectorum* the primary weed species again.

S. iberica was not a serious problem in the WWF rotation as population density did not exceed 2 plants m^{-2} at the harvest assessment on either east or west plots and no difference was detected among crop years (Table 4). In addition, *S. iberica* plants were small following harvest and did not require a postharvest herbicide application. At the late-winter assessment, *S. iberica* was present only at the east site (Table 4). When germination did occur, seedlings typically were found under residue from the previous crop where they were protected from frost.

3.3.2. No-till spring wheat/chemical fallow

Initial west SWF weed density was low (Table 5) because of the long fallow period between the 1994 winter wheat crop and the 1996 spring crop. The extended fallow period was effective apparently in reducing the weed seed bank as in-crop herbicides were not applied to the 1996 spring wheat crop. This trend continued into the first late-winter assessment (1997) where total weed density was 85% volunteer crop (Table 5). Total weed density was similar the first 3

Table 5
Weed density and species richness in a SWF at two adjacent field sites, west and east in a 6-year cropping system study[a]

	Major weed species (weed density m^{-2})[b]							Total density	Species richness[c]
Year	BROTE	SASKR	LACSE	CHELE	DESSO	SSYAL	Vol.		
West field site									
Late-winter prefallow/preplant assessment									
1997	6 b	0 c	0 d	0 b	T b	9 a	101 a	119 b	2.0 c
1998	5 b	T ab	9 b	T b	7 ab	T c	T d	25 bc	3.7 b
1999	5 b	3 a	1 c	5 a	5 ab	2 bc	33 b	68 bc	5.4 a
2000	183 a	1 ab	165 a	0 b	97 a	5 ab	4 c	592 a	3.9 b
2001	0 c	T bc	0 d	T b	T b	2 bc	7 c	12 c	2.5 c
Spring in-crop assessment									
1996	T a	T a	T b	0 b	0 b	0 a	0 a	T c	2.3 a
1998	0 a	T a	T a	T a	T ab	T a	0 a	4 b	1.7 a
2000	T a	2 a	7 a	T a	1 a	T a	0 a	17 a	3.6 a
Harvest assessment									
1996	0 a	T a	T a	T a	0 a	0 a	0 a	1 a	0.6 a
1998	0 a	2 a	T a	T a	T a	0 a	0 a	2 a	0.7 a
2000	T a	T a	T a	0 a	0 a	0 a	0 a	2 a	0.9 a
East field site									
Late-winter prefallow/preplant assessment									
1996	225 b	—	—	—	—	—	—	—	—
1997	803 a	0 b	0 b	0 b	T a	T b	0 b	807 a	1.3 b
1998	82 bc	T ab	T ab	T b	T a	T ab	49 a	138 bc	3.7 a
1999	5 d	0 b	T ab	0 b	0 a	T b	T b	7 d	0.8 b
2000	291 b	4 a	2 a	13 a	3 a	11 a	50 a	400 ab	5.0 a
2001	29 cd	T b	T ab	0 b	T a	T b	0 b	30 cd	1.5 b
Spring in-crop assessment									
1997	T ab	18 a	T a	T a	0 a	T a	0 a	22 a	2.4 a
1999	2 a	7 ab	T a	T a	0 a	0 a	0 a	11 ab	2.3 a
2001	T b	2 b	T a	T a	0 a	0 a	0 a	2 b	1.4 a
Harvest assessment									
1997	3 a	15 a	0 a	0 a	0 a	0 a	0 a	18 a	1.8 a
1999	3 a	5 a	0 a	T a	0 a	0 a	0 a	7 a	1.8 a
2001	T b	T b	0 a	0 a	0 a	0 a	0 a	T b	0.2 b

[a] Means in each column within assessment and site followed by the same letter are not significantly different ($P \leqslant 0.05$).

[b] For abbreviations see Table 3.

[c] Species richness is the mean number of species occurring each year.

years, 1997, 1998, and 1999, which suggested no real change in weed pressure; however, species richness increased each of the 3 years, which indicated the weed flora responded to the new rotation. Weed population unexpectedly rose in the 2000 late-winter assessment. The population averaged 592 weeds m^{-2} and consisted primarily of *B. tectorum*, *L. serriola*, and *D. sofia* (Table 5). These weeds were controlled with a herbicide prior to spring planting.

In-crop total weed density in west SWF increased each year to a high of 17 plants m^{-2} in 2000 with *L. serriola* and *S. iberica* comprising 41% and 12% of the total, respectively (Table 5). Difference in weed-species richness at the in-crop assessment was not detected. At each harvest assessment, total weed density and species richness did not differ between years and reflected low overall weed presence (Table 5). Although no differences occurred among years for any of the weeds listed, relatively few individuals of species found at the harvest assessment could provide additions to the seed bank. At the 2000 harvest assessment, 13 *C. canadensis* plants m^{-2} were counted in one plot and most likely produced viable seed (data not shown).

Total weed density in east SWF was greatest at the beginning of the research and contrasted with the west SWF (Table 5). Following the grower's 1995 east-side winter wheat harvest, *B. tectorum* germinated after October precipitation. Mean density was 705 plants m^{-2} (data not shown) and, consequently, atrazine herbicide was applied to control these seedlings and to suppress additional establishment through the winter. In the following 1996 late-winter (prefallow) assessment, 225 *B. tectorum* plants m^{-2} were present, either as new recruits or escapes from the atrazine treatment (Table 5). *B. tectorum* was the only weed counted in 1996 and was the primary weed present in the assessment. By the 1997 late-winter (preplant) assessment, *B. tectorum* increased to 803 plants m^{-2}. In addition, *B. tectorum* was the most prevalent weed at each of the late-winter assessments with volunteer wheat a distant second in 1998 and 2000, probably from seed lost from each previous year's harvest.

Species richness at the east late-winter assessments was greatest in 1998 and 2000 and averaged 3.7 and 5.0 species, respectively (Table 5). Density of all species were generally greater in 2000 compared to 1998; however, there was no difference between 1998 and 2000 for any species except *C. leptophyllum*. Environmental conditions in winter 2000 may have been more favorable for germination of a broad range of weed species as evidenced by a greater total weed population, but variation among replications was too great to find differences.

Within the in-crop assessments, species richness was similar for the 3 years (Table 5) and resulted from emergence of the same small group of species following the preplant glyphosate application. The most prevalent weed was *S. iberica*, which comprised 82%, 64%, and nearly 100% of the 1997, 1999, and 2001 assessments, respectively (Table 5). However, *S. iberica* density, which was greatest during the first crop year, declined significantly by the 2001 crop. Reducing soil disturbance that stimulates *S. iberica* germination was likely a factor in the decline. A sparse density of *B. tectorum* was present at the in-crop assessments. Grass-weed herbicides were not applied to spring cereal crops; therefore, *B. tectorum* seedlings present at the in-crop assessment probably produced seed by crop harvest.

At each harvest assessment, *S. iberica* and *B. tectorum* were the only weeds present, except for a few *C. leptophyllum* in 1999 (Table 5). Within each species, density was similar for the 1997 and 1999 assessment even though *S. iberica* appeared more prevalent in 1997. By 2001, only a few individuals of either weed remained. Species richness at the harvest assessment was least in 2001 and resulted from better overall in-crop weed control, as well as an overall decrease in weed pressure during the three crop rotation cycles. Total weed density declined from 18 plants m^{-2} in 1997 to only a trace in 2001 (Table 5).

3.3.3. No-till CSC

Very few weed species were present in the west CSC rotation both in the first year 1996 in-crop assessment and in the 1997 late-winter assessment (Table 6). Eighty-eight percent of the plants present were volunteer crop in the 1997 late-winter assessment. Species richness increased by the second year in the late-winter assessment as more dicot weeds were present. The greatest total weed density of the late-winter assessment occurred in 2000 but was primarily volunteer crop. Very few *B. tectorum* were present, which was significantly less than all other years (Table 6). Volunteer crop density was high at this assessment and may have competed with *B. tectorum*. By the final year of the research, total weed density declined to its lowest number while species richness still remained relatively high. At the in-crop and harvest assessments, species richness was low in all years even though some differences occurred. *S. iberica* was most prevalent at the in-crop assessment during the third, fourth, and fifth rotation cycles but declined by the last cycle, with only trace amounts of other weeds present. At the harvest assessment, the west CSC plots were nearly weed free, especially by the last year of the research.

The effect of the no-till CSC rotation on weed density was especially noticeable on the east side as initial weed density was high and dominated by *B. tectorum* (late-winter preplant) and *S. iberica* (in-crop). At the late-winter assessment, *B. tectorum* declined steadily from 914 plants m^{-2} in 1996 to only a few individuals in 2001 (Table 6). There were few changes in densities of the

Table 6
Weed density and species richness in a CSC rotation at two adjacent field sites, west and east in a 6-year cropping system study[a]

	Major weed species (weed density m^{-2})[b]							Total density	Species richness[c]
Year	BROTE	SASKR	LACSE	CHELE	DESSO	SSYAL	Vol.		
West field site									
Late-winter preplant assessment									
1997	5 a	0 c	0 c	0 b	1 a	2 ab	83 b	94 b	1.7 b
1998	3 a	T b	2 ab	T a	T a	1 ab	31 c	39 c	3.9 a
1999	4 a	T bc	1 b	0 b	T a	T b	9 d	17 d	3.1 a
2000	T b	2 a	9 a	0 b	4 a	3 a	154 a	180 a	3.3 a
2001	5 a	T bc	2 b	0 b	T a	T b	26 c	35 c	3.4 a
Spring in-crop assessment									
1996	0 a	T bc	T c	T a	T a	0 b	0 a	T b	1.5 a
1997	T a	T bc	T abc	T a	T a	0 b	0 a	T bc	0.5 b
1998	0 a	8 a	T ab	T a	T a	T ab	0 a	10 a	1.1 ab
1999	T a	2 ab	T a	T a	T a	T ab	T a	3 abc	1.1 ab
2000	T a	3 ab	T a	T a	T a	T a	T a	5 ab	1.6 a
2001	0 a	0 c	T bc	T a	T a	T ab	T a	T c	0.5 b
Harvest assessment									
1996	0 a	T ab	T a	T a	T a	0 a	0 a	1 ab	0.6 a
1997	T ab	T ab	0 a	0 b	0 a	0 a	0 a	T ab	0.1 a
1998	T a	1 a	T a	0 b	0 a	0 a	0 a	3 a	0.5 ab
1999	T ab	T ab	0 a	0 b	0 a	0 a	0 a	T ab	0.2 ab
2000	T ab	T ab	T a	0 b	0 a	0 a	0 a	T ab	0.2 ab
2001	T ab	0 b	0 a	0 b	0 a	0 a	0 a	T b	0.05 b
East field site									
Late-winter preplant assessment									
1996	914 a	—	—	—	—	—	—	—	—
1997	518 a	0 b	0 c	0 a	T b	T b	9 b	298 a	1.5 c
1998	157 b	T b	3 a	T a	T ab	T ab	37 a	205 a	3.9 a
1999	7 cd	2 a	T b	0 a	T b	T b	7 b	17 b	3.0 ab
2000	11 c	2 a	3 a	0 a	4 a	4 a	67 a	95 ab	3.6 a
2001	T d	T b	1 b	T a	T ab	T b	10 b	14 b	2.4 bc
Spring in-crop assessment									
1996	4 a	19 ab	T a	T b	0 a	T ab	0 a	25 ab	3.2 a
1997	4 a	7 b	T a	T a	T a	0 b	0 a	14 bc	2.4 ab
1998	T b	54 a	T a	T a	T a	T ab	0 a	56 a	2.2 b
1999	0 bc	6 bc	T a	T a	T a	T ab	T a	7 bcd	1.6 bc
2000	0 a	4 bc	T a	T a	0 a	T a	0 a	6 cd	1.7 bc
2001	0 a	T c	T a	T a	0 a	T ab	T a	2 d	0.8 c
Harvest assessment									
1996	5 a	1 ab	0 a	T a	0 a	0 a	0 a	7 a	0.4 bc
1997	7 a	4 a	0 a	T a	0 a	0 a	0 a	12 a	1.8 a
1998	T ab	9 a	0 a	0 a	0 a	0 a	T a	12 a	0.7 b
1999	T b	T c	0 a	0 a	0 a	0 a	0 a	T b	0.2 c
2000	0 b	T bc	0 a	0 a	0 a	0 a	0 a	T b	0.1 c
2001	T b	T bc	0 a	0 a	0 a	0 a	0 a	T b	0.1 c

[a] Means in each column within assessment and site followed by the same letter are not significantly different ($P \leqslant 0.05$).

[b] For abbreviations see Table 3.

[c] Species richness is the mean number of species occurring each year.

other weeds present and none of real consequence; however, with the decline of *B. tectorum*, species richness increased initially for three rotation cycles, then declined as occurrence of all weeds was intermittent. At the in-crop assessment, a few *B. tectorum* were present during the first two rotation cycles, but none were evident by the final three cycles (Table 6). During the first 3 years, *S. iberica* was most prevalent in the in-crop assessment, reaching a high of 54 plants m^{-2} in 1998, but declined in density in the final 3 years. However, a few *L. serriola* and *C. leptophyllum* consistently appeared in the in-crop assessment. At the harvest assessment, total weed density was greater during the first 3 years of the research and was composed primarily of *B. tectorum* and *S. iberica* (Table 6). During the final 3 years of the research, weed density was zero for all weeds except *B. tectorum* and *S. iberica*, which were only observed in trace amounts.

In addition, species richness was also nearly zero and reflected the near weed-free condition of the plots.

3.4. Comparisons between crop rotation using total weed density

Total weed density was generally higher at the late-winter assessment compared with the in-crop or harvest assessments (Table 7). During the first 3 years of the research, east plots tended to have more weeds than west plots at the late-winter assessment. The exception to this was the east WWF in 1998, where total weed density was not different from west rotations. During the last 3 years, west WWF had the highest total weed density in both 1999 and 2001. In 2000, weed densities were high in SWF plots (Table 7); however, differences could not be detected between CSC plots and east SWF, or between east CSC and east SWF because of high variation in the counts. In addition, east WWF had fewer weeds than either east or west SWF.

At the in-crop assessment, total weed density was highest in both east and west WWF rotations (Table 7). As the research progressed, the magnitude of difference between WWF and spring-crop rotations appeared to be greater for west than for east plots. For example, total weed density in 2000 west WWF was 368 plants m^{-2} compared with 17 plants m^{-2} for west SWF (Table 7). In 2001, east WWF plots averaged 24 plants m^{-2} while the east SWF and CSC rotations averaged only 2 weeds m^{-2}. This trend also was observed at the harvest assessment where highest densities were generally found in the WWF rotations (Table 7). During the last 3 years of the research, CSC rotations had only a few weeds. In the final year of the research, no differences were detected at the in-crop assessment as only trace numbers were counted in any of the rotations, including east WWF.

4. Discussion

Management and rotation were the major factors affecting weed populations over the 6-year study. This assessment agrees with Doucet et al. (1999), who found that management has a much greater impact (37%) on weed density than rotation alone (5.5%). In the WWF rotations, management of east plots was focused more on reducing the initial high density of *B. tectorum* and resulted in its decline through the course of the research (Table 4). In the west plots, *B. tectorum* was consistently dense at each of the late-winter assessments and increased each year in the in-crop and harvest

Table 7
Evaluation of crop rotation effect on total weed density (m^{-2}) comparing WWF, SWF, and CSC for each of 6 years of a cropping system study. Each rotation was included in two adjacent field sites labeled west site and east site[a]

Rotation/site	1996[b]	1997	1998	1999	2000	2001
Late-winter assessment[c]						
WWF—West	—	549 a	—	317 a	—	385 a
WWF—East	601 a	.	44 bc	—	32 c	.
SWF—West	—	119 b	25 c	68 b	592 a	12 b
SWF—East	225 b	807 a	138 ab	7 c	400 ab	30 b
CSC—West	—	94 b	39 bc	17 c	180 abc	35 b
CSC—East	914 a	298 ab	205 a	17 c	95 bc	14 b
Spring postemergence in-crop assessment						
WWF—West	14 a	—	155 a	—	368 a	—
WWF—East	—	137 a	—	31 a	—	24 a
SWF—West	T b	—	4 b	—	17 b	.
SWF—East	—	22 b	—	11 ab	—	2 b
CSC—West	T b	T c	10 b	3 b	5 b	T b
CSC—East	25 a	14 b	56 a	7 ab	6 b	2 b
Harvest assessment						
WWF—West	13 a	–	39 a	–	143 a	–
WWF—East	–	51 a	–	12 a	–	T a
SWF—West	1 c	–	2 b	–	2 b	–
SWF—East	–	18 b	–	7 ab	–	T a
CSC—West	1 c	T c	3 b	T bc	T bc	T a
CSC—East	7 b	12 b	12 ab	T c	T c	T a

[a] Means within each year and assessment followed by the same letter are not different at the $P \leqslant 0.05$ level of significance.

[b] In 1996, only *B. tectorum* was included in the west SWF and all late-winter assessments, but was the primary species present.

[c] Weed counts during even years in west SWF, odd years in east SWF, and all years in CSC were prior to preplant herbicide applications. All other counts were at the beginning of a fallow year.

assessments. East-side management included a light disking to incorporate weed seeds after each harvest and use of a split fall/spring grass-weed herbicide application during the first crop cycle followed by single applications in the second and third cycles. Furthermore, the reseeding of a failed winter wheat crop was delayed until a dense flush of *B. tectorum* was controlled that had emerged following the soil-crusting rain. *B. tectorum* germinated considerably later than the reseeded crop germinated that fall and probably was less competitive with the crop (Rydrych, 1974) and susceptible to metribuzin because of the early stage of growth.

Our research shows that reduction of *B. tectorum* in a 2-year rotation is possible with intense management for at least three consecutive cycles. This contrasts with other research that suggests *B. tectorum* reduction requires at least a 3-year rotation (2 years out of winter wheat) (Lyon and Baltensperger, 1995; Young et al., 1996). Because our WWF system also greatly reduced the number of tillage operations compared to the traditional WWF of the region (Thorne et al., 2003), adoption of our WWF system with intense weed management would also reduce wind erosion susceptibility.

Weed populations through the course of the study were generally lower in no-till CSC rotations than in WWF (Table 7). *B. tectorum* populations were reduced greatly as a result of the annual late-winter glyphosate applications that kept the number of plants producing seed in the crop at a minimum. In the first two crop years of the east SWF and CSC rotations, as many as 900 *B. tectorum* plants m^{-2} were present in late-winter (Table 6), but by the harvest assessment, as few as 3 plants m^{-2} persisted (Table 5).

In the arid and semi-arid regions of the Pacific Northwest, *B. tectorum* germinates primarily in September and October following fall rains; however, germination can occur during winter months when soil temperature is as low as 0°C, and in spring until mid-May (Mack and Pyke, 1983). Furthermore, a large proportion of each year's seed crop germinates, decomposes, or is consumed by granivores (Mack and Pyke, 1983; Crist and Friese, 1993). In our research, seedlings that germinated in the fall and survived through the winter were controlled with the late-winter glyphosate application. *B. tectorum* seedlings counted in the no-till in-crop assessment could have been either escapes from the preplant glyphosate application or new recruits that emerged following the glyphosate application. These plants likely produced some viable seed but far less in number than a fully tillered fall-germinated plant typically found in WWF. In the east CSC rotations, *B. tectorum* appeared in the harvest assessment by the third crop year and a trace was counted in the 2001 late-winter assessment (Table 6), suggesting that a few individuals were adding seeds to the seed bank.

In the west spring-crop rotations, weed density was low at the beginning of the research and no difference in total weed density could be detected between east and west spring-crop rotations at each of the three assessments at the final year of the study (Table 7). However, weed density in SWF and CSC increased in the 2000 late-winter assessment. In 2000, total weed density averaged 592 m^{-2} in west SWF at the late-winter assessment with *B. tectorum* and *L. serriola* as the major species (Table 5). This was a significant increase from the previous year's 68 weeds m^{-2} (Table 7), and likely occurred because of weed seeds produced in the previous fallow year when the initial chemical-fallow herbicide application was delayed until June. Likewise, an increase in *B. tectorum* and volunteer crop in the 2000 east SWF late-winter assessment (Table 5) was likely from seed produced during the 1999 crop cycle. Increases in weed density in CSC rotations in 2000 were primarily a result of an increase in volunteer crop; however, some dicot weeds also increased. Winter weed mortality may have been less because the 1999–2000 winter was the warmest of the 6 years.

These slight increases in weed populations suggest that no-till weed management must include strategies to maintain weeds at the lowest populations possible because favorable environmental conditions can lead to major infestations in subsequent years. Rydrych and Muzik (1968) showed that survival of only 10% of the previous year's seed crop of *B. tectorum* can readily lead to a high-density infestation of up to 444 plants m^{-2} the following year. It is also apparent that the SWF may be more vulnerable to weed problems than annual spring-crop rotations where crop competition occurs and herbicides are routinely applied preplant and in the growing crop. In no-till cropping systems, weed seeds tend to accumulate on the soil surface (Yenish et al., 1992; Clements et al., 1996); therefore, weed density can quickly reflect the previous year's seed production. Also, in our chemical fallow, the initial herbicide application was often delayed because of economics and weather to allow the highest number of weeds to germinate as possible before spraying. Therefore, some of the early germinating weeds may have produced viable seeds.

In the no-till spring crop rotations, *S. iberica* populations were typically very low. Accumulated surface residue and lack of soil disturbance (Thorne et al., 2003) may have been major factors in suppressing *S. iberica* population in the spring crops. Young (1986, 1988) has shown that *S. iberica* is a major problem for spring wheat and barley in the WWF region of the eastern Washington. In our research, herbicide was applied postharvest for *S. iberica* control only in the first years of the research but was not needed toward the end of the project. This suggests that *S. iberica* may not be as great a problem in no-till spring crop rotations as it is in tillage-based spring crops and that an intense weed management program (preplant, in-crop, and postharvest) reduced *S. iberica* populations. This agrees with Derksen et al. (1993), who found that summer-annual dicot weeds were more closely associated with conventional tillage than no-till. An exception to this may be in SWF rotations if chemical-fallow weed management does not inhibit *S. iberica* and other dicot weeds from producing seed.

Future weed management concerns for no-till spring cropping in the traditional WWF region include species such as the wind-dispersed *L. serriola*, and *C. canadensis*, and annual grass weeds such as *Avena fatua* L. Wind-dispersed dicot weeds, *C. canadensis*, in particular, are associated with no-till systems (Derksen et al., 1993) and will likely be a major weed problem in long-term, no-till spring-crop rotations in the Pacific Northwest. In our research, *C. canadensis* appeared in SWF in the 2000 harvest assessment (data not shown) and *L. serriola* was found in all in-crop assessments (Tables 5 and 6). Furthermore, both these species are commonly found in roadside and non-crop areas in the semi-arid region of the Pacific Northwest. Because our research sites were at least 30 m from field borders, plots were somewhat protected from seeds blowing in from adjacent areas; however, this is not the case for most fields of the region.

Although spring-germinating grass weeds such as *A. fatua* were not found in our no-till CSC plots, these weeds can persist in other no-till cropping regions of North America (Dale et al., 1992; Derksen et al., 1993) including the nearby Palouse region of the Pacific Northwest where rainfall is higher and annual spring crops are an integral part of contemporary conservation-tillage rotations (Young et al., 1994, 1996).

5. Conclusions

The results from this research show that weed management within no-till spring crop and traditional WWF rotations can significantly reduce weed population density in the semi-arid WWF region of the Pacific Northwest USA. Reduction of weed populations in no-till rotations resulted from controlling *B. tectorum* and other winter-annual weeds with preplant or prefallow herbicide applications. In addition, lack of tillage, which suppressed invasion of summer-annual dicot weeds, and use of postharvest herbicide applications kept *S. iberica* from becoming a major problem. However, potential problems from other wind-dispersed weeds such as *L. serriola* and *C. canadensis* were beginning to appear toward the end of the research. Weed management for no-till systems in this region should assertively focus on keeping weeds from producing seed in the crop or during chemical fallow.

In WWF, more intensive management using light tillage to encourage germination for subsequent herbicide control of *B. tectorum*, in combination with in-crop grass-weed herbicides dramatically reduced *B. tectorum* density compared with less intense management. By the end of the research, only trace numbers of weeds were found at crop harvest in the more intensively managed WWF plots, and these densities were similar to the weed density reductions in no-till spring crop rotations.

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