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ScienceDirect
Crop Protection 26 (2007) 1121–1134
Crop Protection
www.elsevier.com/locate/cropro

# Cropping systems alter weed seed banks in Pacific Northwest semi-arid wheat region

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Received 22 August 2006; accepted 9 October 2006

**Abstract**

Arable land weed seed banks are dynamic and reflect cropping history, current management, and environment. Changes in crop rotation and tillage system can alter weed seed density and species composition. In the semi-arid region of the Pacific Northwest, USA, no-till spring cropping is being studied as an alternative to the traditional winter wheat (*Triticum aestivum* L.)/dust-mulch fallow (WWF) rotation. Weed seed bank density and species composition were assessed during the first 6 years of an ongoing cropping system study comparing WWF with three no-till rotations; spring wheat (*Triticum aestivum* L.)/chemical fallow (SWF), continuous spring wheat (CSW), and spring wheat/spring barley (*Hordeum vulgare* L.) (SWSB). Soil cores were collected at depths of 0–8, 8–15, and 15–23 cm in all plots during August each year following crop harvest. Weed seeds were washed from the soil, dried, and germinated in a glasshouse. Weed species most associated with the 0–8 cm depth was *Bromus tectorum* L., the major winter annual grass weed in WWF. Species most associated with 8–15 cm depth was *Chenopodium leptophyllum* (Moq.) Nut. ex S. Wats, a native warm season broadleaf weed that may have long seed bank persistence. An initial high density of *B. tectorum* was reduced with no-till spring crops and in WWF with intensive management strategies. In comparison an initial low weed seed density of *B. tectorum* remained low with no-till but increased in WWF with less management. Broadleaf weed species did not become management problems in no-till; however, seed bank weed shifts occurred where winter annual broadleaf species remained following reduction of high densities of *B. tectorum*. Summer annual broadleaf weed seeds such as *C. leptophyllum* and *Salsola tragus* L. were present but not at high densities. Summer annual grass weed seeds were not present and are not typical in this region. In this research, no-till spring cereal based systems did not result in an increase in total seed density at the soil surface. Results from this research show that no-till spring crop rotations are effective at controlling winter annual grass weeds as well as broadleaf weeds normally associated with WWF.


*Keywords:* Seed banks; Weed shifts; No-till cropping; Winter wheat; Dust-mulch fallow; Chemical fallow; Pacific Northwest

## 1. Introduction

Changes in weed seed bank density and species composition often occur when cropping strategies are altered (Cardina et al., 1991, 2002; Clements et al., 1996). Weed seed bank research has generally found that no-till cropping systems have greater weed density, diversity, or both, compared with tillage-based systems (Cardina and Sparrow, 1996; Menalled et al., 2001; Cardina et al., 2002; Tørresen and Skuterud, 2002; Davis et al., 2005). Lack of soil disturbance in no-till systems causes seeds to accumulate at the soil surface (Yenish et al., 1992; Hoffman et al., 1998) and selects for species that can germinate from shallow depths or from within the surface residue layer (Bàrberi and Lo Cascio, 2001). In contrast, tillage systems disperse seeds throughout the tillage profile (Ball, 1992; Yenish et al., 1992; Clements et al., 1996) and tend to favor species that require soil disturbance. Froud-Williams et al. (1983) found that annual broadleaf species were more prevalent on tilled plots, and that wind disseminated and grass species are more prevalent on untilled plots.

However, factors other than tillage or rotation regime can affect seed bank density and composition. Buhler et al.

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doi:10.1016/j.cropro.2006.10.021

(1997) noted that species composition can vary due to local environmental conditions and farming practices that influence seed production, seed loss or mortality, and seed carry over to the next crop. Cardina et al. (2002) at a site in Ohio, USA, found the relative importance of *Chenopodium album* L., a small-seeded dicotyledonous (broadleaf) weed, higher in no-till plots compared with chisel plow or moldboard plow plots. At a second site with the same rotation and tillage practices, but with a different cropping history, they found *Setaria faberi* L., a warm season grass, had the highest relative importance in no-till and chisel plow, but not in moldboard plow. Buhler (1999) found increased seed densities from dry soil conditions that reduced herbicide efficacy, and from wet conditions that reduced effectiveness and timing of tillage treatments. Therefore, given the variable nature of arable land seed bank composition and diversity, it may be difficult to accurately predict changes in weed flora when cropping systems are changed.

In the semi-arid ($<300\,\mathrm{mm\,yr^{-1}}$) Columbia Plateau region of the Pacific Northwest, USA, no-till farming has the potential to reduce wind-borne soil erosion emanating from exposed soil during the dust-mulch fallow phase of the traditional winter wheat/fallow rotation. This reduction occurs primarily as crop residues are retained on the soil surface (Horning et al., 1998; Papendick, 1998; Thorne et al., 2003). Traditional winter wheat production relies on a year of dust-mulch fallow to retain soil moisture near the soil surface so that crop emergence can occur soon after planting in late summer or early fall (Schillinger and Papendick, 1997). Without the stored soil moisture, wheat seeds do not germinate until after late-fall rains, plants are small going through the winter, and yields are reduced in the following harvest (Donaldson et al., 2001).

No-till spring crop production would eliminate the need for the dust-mulch, thus reducing much of the wind-borne soil erosion; however, changes in cropping systems would also bring about changes in weed management. Weeds problematic for winter wheat in this region are *Bromus tectorum* L. and *Salsola tragus* L. *B. tectorum* is a winter annual grass that competes vigorously with winter wheat and can cause substantial wheat yield loss, especially when it germinates within 21 d of wheat emergence (Rydrych, 1974; Blackshaw, 1993). Occurrence of *B. tectorum* should decline in no-till spring crops since plants established through the fall and winter can be controlled with a herbicide prior to seeding. Furthermore, most *B. tectorum* seeds do not persist more than a year following dispersal in August (Wicks, 1997). *S. tragus* is a summer annual dicotyledonous (broadleaf) species that is most problematic in spring crops but can also be a problem for winter wheat (Young, 1988; Schillinger and Young, 2000).

To date, there have been no weed seed bank studies in the semi-arid winter wheat region of the Pacific Northwest. We hypothesized that broadleaf species already in the seed bank are the most likely candidates to become immediate weed problems in no-till spring crops; however, seed banks associated with the current winter wheat system may not contain species best adapted to no-till spring cropping systems. Species common to the mesic Palouse region of eastern Washington and northern Idaho, such as *Avena fatua* L. or *Chenopodium album* L., or warm-season species associated with irrigated cropland of the Columbia Basin, such as *Setaria* spp. or *Kochia scoparia* (L.) Scrad., may become prevalent in no-till spring crop systems in the semi-arid region.

The objectives of this study were to describe the composition of weed seed banks associated with traditional winter wheat production and no-till cropping systems in the semi-arid region of the Pacific Northwest, USA. Specifically, we evaluated seed bank density and composition in reduced-tillage WWF and three no-till crop rotations over 6 years. The overall intent is to develop knowledge of seed bank dynamics in this region so that weed problems associated with no-till cropping can be understood and managed proactively. Furthermore, knowledge of seed bank composition and dynamics may also aid weed management in current winter wheat production.

## 2. Materials and methods

The weed seed bank was assessed as a component of an ongoing large-scale cropping system study analyzing the potential of no-till cereal rotations for the semi-arid winter wheat production region of the Pacific Northwest, USA. The 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, similar and relatively level field sites. Soil in both field sites is a Ritzville silt loam (coarse silty, mixed, mesic, Calcidic Haploxeroll) with a texture of 30% sand, 62% silt, and 8% clay. Organic matter in the top 30 cm averaged 2.0% and 1.9% in east and west sites, respectively. In the summer of 1995, the east site was in standing wheat stubble and the west site was in dust mulch fallow. Four crop rotations were established in each site and were (1) traditional winter wheat (*Triticum aestivum* L.)/dust-mulch fallow (WWF), (2) no-till spring wheat (*T. aestivum* L.)/chemical fallow (SWF), (3) no-till continuous hard-red spring wheat (CSW), and (4) no-till hard-red spring wheat/spring barley (*Hordeum vulgare* L.) (SWSB). Sixteen $9\times152$ m plots were established in each field site in a randomized complete block design with each rotation replicated four times per field site. By using the two adjacent field sites, the no-till rotations could be established in both phases of WWF simultaneously. In the initial crop year (1995–1996), east WWF and SWF rotations were in the fallow phase and SWSB was in the spring barley phase. Concurrently, west WWF and SWF rotations were in the crop phase and SWSB was in the spring wheat phase. The CSW rotation was in spring wheat in both field sites each year of the study.

Precipitation was recorded on-site between 1995 and 2000 and reported annually on a crop year (1 September–31 August) basis. The long-term average for the study site, reported by the grower, is approximately 305 mm year$^{-1}$. Precipitation recorded for 1995–96, 1996–97, 1997–98, 1998–99, and 1999–00 crop years was 357, 427, 327, 243, and 269 mm, respectively, and averaged 324 mm during the study period.

### 2.1. Crop management

Detailed crop management operations within this study have been previously published (Young and Thorne, 2004; Thorne et al., 2003). Briefly, the traditional dust-mulch fallow rotations were managed in accordance with the cooperator's standard farming procedures and were congruent with conservation farming principles of the region. Field operations were conducted with non-inversion implements to leave crop residue on the soil surface to prevent wind erosion. Primary tillage and fertilization for summer fallow was in April or May following the previous year's winter wheat harvest using a V-shaped sweep-blade implement to undercut the stubble to a depth of 13 cm. Secondary tillage killed weeds and sealed the dust mulch, thus reducing soil moisture loss. Soft-white winter wheat Lewjain cv. or Rely cv. was planted in September or early October of the fallow year using a John Deere® deep-furrow drill with 40-cm spacing that placed seeds in the moist seedbed underlying the dry dust mulch. In 1996, the east WWF plots were reseeded in October because a September rain crusted the soil and prevented the wheat seedlings from emerging. However, continued precipitation caused a flush of *B. tectorum* seedlings to emerge, which were subsequently killed with tillage prior to reseeding. Wheat seedlings emerged within 14 d following re-seeding.

No-till crops were planted with a John Deere® hoe-opener drill with 18-cm spacing in March or April of each year. Soft-white spring wheat Alpowa cv. was planted in the SWF rotation, while hard-red spring wheat Butte 86 cv. or Scarlet cv. and two-row spring barley Baronnesse cv. were planted in the CSW and SWSB rotations. For the hard-red spring wheat, fertilizer was split-applied in the fall and in the spring at planting. The soft-white spring wheat and spring barley crops were fertilized only at planting. Fertilizer rates were adjusted each year based on post-harvest and pre-plant soil tests and over-winter precipitation.

For weed control, all plots, except those with a growing winter wheat crop, were sprayed with glyphosate in early March to kill annual weeds that emerged through the fall and winter. The SWF rotation plots were sprayed with glyphosate and 2,4-D amine as needed during the fallow year to kill spring and summer emerging weeds. In the WWF rotation, either metribuzin or sulfosulfuron were used for grass weed control in the crop, while 2,4-D amine was used for broadleaf weeds. In the spring crops various herbicides (MCPA, bromoxynil, 2,4-D amine, tribenuron, thifensulfuron, and dicamba) were applied for broadleaf weed control depending on species and environmental factors. Herbicide rates were consistent with product labels and were rotated to prevent weed resistance. When needed, SWF, CSW, and SWSB plots were sprayed with paraquat + diuron herbicide following harvest to kill *S. tragus* plants to conserve soil moisture and prevent seed production.

All plots were harvested with a farm-size John Deere® harvester equipped with an on-board scale to measure grain yield. The harvester had a chaff spreader and straw chopper to spread crop residue and weed seeds more evenly across the width of the harvest pass. Furthermore, all other field operations were conducted with farm-sized equipment so that results from the research would be applicable to farms in the region.

### 2.2. Seed bank assessment

Seed banks were assessed using a direct glasshouse germination procedure similar to that of Gross (1990) and Thompson and Grime (1979). However, the process differed in that weed seeds were first extracted from each sample using an elutriation technique similar to Gross and Renner (1989), and prior to germination, seeds were treated with gibberellic acid and $KNO_3$.

Soil samples were collected in all plots, including those in fallow, during August and early September following crop harvest in 1995 and continuing through 2000. In each $152 \times 9$ m plot, 19 samples were collected in 1995 and 1996, and 20 samples in 1997–2000. Samples were collected systematically at 6 m intervals within each plot, alternating 1 m from either side of a centerline. Soil sample diameter was 3.2 cm in all years except 1996, where diameter was 1.9 cm. Each soil sample was divided into 0–8, 8–15, and 15–23 cm depths, and combined by depth increment for each plot. Samples were transported in coolers on ice and stored in a freezer at −18 °C until processing.

Weed seeds were extracted from the soil by placing a sample in a 500 μm sieve and washing with water until soil was removed. The silt loam was easily removed and washing time was no longer than 180 s per sample. Following washing, seeds and debris were backwashed from the sieve through a large funnel and collected in a standard automatic-drip coffee filter. The filter and seeds were squeezed by hand to remove excess water, placed in a small paper bag, oven dried at 30 °C for 30 d, and stored in a freezer at −18 °C until germination.

Prior to germination, samples were put in 0.25 l plastic beakers and pre-soaked 2 h in a 0.34 mmol gibberellic acid and 0.1 mmol $KNO_3$ solution to aid in germination; solution volume was approximately 0.1 l but was adjusted so that all debris were covered. For samples taken in 1995, seeds were soaked only in a 1.0 mmol gibberellic acid solution. The $KNO_3$ was added specifically to aid in *S. tragus* germination (Young and Evans, 1979). Pre-soaked seeds were then spread evenly over the top of soil-less potting mixture in a $52 \times 26 \times 6$ cm plastic flat (Hummert International F1020) and then covered with a thin layer of expanded vermiculite. Each flat was placed inside an open ended plastic bag to retain moisture during initial germination. Flats were kept in a controlled environment glasshouse with a temperature maximum of 22 °C and a minimum of 16 °C. Artificial light was used to augment natural light in maintaining a 14 h light period. After 30 d, seedlings were counted and then sprayed with a glyphosate solution containing 6 g $l^{-1}$ active ingredient at a spray rate of 73 l $ha^{-1}$. After the initial seedling flush died, aboveground biomass was removed and flats were re-wetted and kept in the glasshouse for an additional 60 d, at which time, seedlings were counted and the growing medium was discarded.

Following germination of 1995 samples, concerns over the effect of wetting and drying on germination of *S. tragus* prompted an additional experiment. Approximately 1000 seeds were given each of the following treatments: (1) no pre-soaking, no drying, (2) 15 min pre-soaking, no drying, (3) 30 min pre-soaking, 48 h drying, and (4) 240 min pre-soaking, 48 h drying. Seeds were pre-soaking in a 1 mmol gibberellic acid solution and dried in a 30 °C oven. Seeds were then placed in flats as described above except without plastic bags. Seedlings were counted when it was apparent that emergence had ceased, at which time, seedlings had developed between 2 and 6 leaves. Each treatment was replicated twice.

Estimation of the weed seed bank was limited to the viable and readily germinable portion and was not intended as a measure of the total seed bank. The elutriation, drying, and freezing procedures as well as pre-soaking seeds in gibberelic acid and $KNO_3$ was intended to satisfy afterripening requirements in some species so that germination in the glasshouse would approximate germination in the field during fall, winter, and spring following crop harvest or fallow. For example, freshly matured *B. tectorum* seeds require a period of high temperature before they will germinate (Thill et al., 1980). This condition is satisfied by normal late summer and fall temperatures prior to the onset of fall rains and cooler temperatures.

### 2.3. Statistical analysis

For analysis and presentation, seedling counts from each plot and depth were converted to a square meter basis. Percent constancy was determined for each species at each of the three depths over the course of the experiment. This was calculated by dividing the number of samples in which a species was observed by the total number of samples and multiplying by 100. Therefore, 100% constancy would occur if a species germinated in all replications, rotations, and years.

The two most frequently occurring and abundant species in this study were analyzed individually with analysis of variance using the GLM procedure of SAS® software (SAS Institute Inc., 1999). Seedling counts of these species were transformed to improve compliance with assumptions of normality and homogeneity of variance by adding 0.375 to the original count and taking the square root (Zar, 1999). Means were back transformed for presentation in tables. Because there was a significant three-way interaction among rotation, year, and depth for both species in the initial analysis, means were compared within each rotation for depth by year combinations using a protected Fisher's LSD test (Ott, 1993).

Multivariate assessments were made with canonical discriminant analysis (CDA) using the CANDISC procedure of SAS® software (SAS Institute Inc., 1999) to assess the relationship between weed seed bank and sample depth, and weed seed bank and crop rotation. Canonical discriminant analysis combines components of principle component analysis and correlation analysis to separate classification variables (rotation and depth in this analysis) based on linear combinations of the quantitative variables (species counts in this analysis) (SAS Institute Inc., 1999). The linear combinations of variables (canonical variables) are then correlated with the original groups. The first canonical variable has the maximum multiple correlation with the classification variables and explains the majority of variation. Output from CANDISC provides both univariate and multivariate analysis of variance. In addition, CANDISK correlates the original quantitative variables with the canonical variables to show which quantitative variables are most associated (loading) with each canonical variable. These loadings are given in the SAS output as "total canonical structure." Canonical variable means (centroid values) are calculated for each classification variable and significance between means is determined using Mahalanobis distance. Either the means or the individual values for each canonical variable can be plotted in a bi-plot. In this research, means for the first and second canonical variable are plotted. Excellent description and use of CDA can be found in Vaylay and van Santen (2002) and Yeater et al. (2004).

Species with constancy values less than 10% were considered rare and were excluded from the CDA analysis. Count data for species included in the CDA, (those with 10% or greater constancy) were transformed using the same technique employed in the univariate analysis above to improve univariate normality for each species as a method to better comply with the assumption of multivariate normality.

Species richness was calculated as the number of species germinating while species diversity was calculated using the Shannon Wiener diversity index (Cardina et al., 1991). Total weed seed density was calculated as the summation of all species, including volunteer crop. Richness, diversity, and total density were analyzed separately with analysis of variance using the GLM procedure of SAS® software (SAS Institute Inc., 1999). These data were in reasonable compliance with normality and homogeneity of variance assumptions and transformation did not improve their overall compliance; therefore, data were not transformed prior to analysis.

## 3. Results

Eleven weed species, not including volunteer wheat and barley, were identified from the soil seed bank assessments. The most prevalent species was *B. tectorum*, which appeared in 57% of all samples at the 0–8 cm depth and 26% and 19% of all samples at the 8–15 and 15–23 cm depths, respectively (Table 1). The second most prevalent species was *Chenopodium leptophyllum*, which had 50% constancy at the 0–8 cm depth and 48% and 29% at the 8–15 and 15–23 cm depths, respectively. The winter annual Brassicaceae species, *S. altissimum* and *Descurainia sophia*, each occurred in about one third of all samples at the 0–8 cm depth while *S. tragus*, one of the regions most problematic broadleaf weeds, occurred in only 15% of samples at the 0–8 cm depth and 0% of the 15–23 cm samples. A separate glasshouse trial to test if the elutriation and drying process would reduce *S. tragus* seed viability found no loss in germination ($P = 0.3329$) (data not shown).

### 3.1. Seed bank distribution by depth

Canonical discriminant analysis found discrimination among all three depths with the 0–8 cm depth farther from the other two depths (Fig. 1). Mahalanobis distances between centroid values for all three depths were significant at the $P < 0.05$ level. The first canonical variable was highly significant ($P \leqslant 0.0001$) and accounted for 92% of the variation (Table 2). The second canonical variable was also significant ($P = 0.001$) but only accounted for 8% of the variation. Weed species associated with the first canonical variable included *B. tectorum* ($r = 0.70$), *S. altissimum* ($r = 0.59$), and *D. sophia* ($r = 0.57$) (Table 2), all of which are winter annuals. For the second canonical variable, *C. leptophyllum*, a summer annual broadleaf, was strongly associated ($r = 0.85$). The 8–15 cm depth aligned at the positive end of the second axis indicating more *C. leptophyllum* seeds at that depth. For analysis presented in Table 2, all years were combined; however, separate

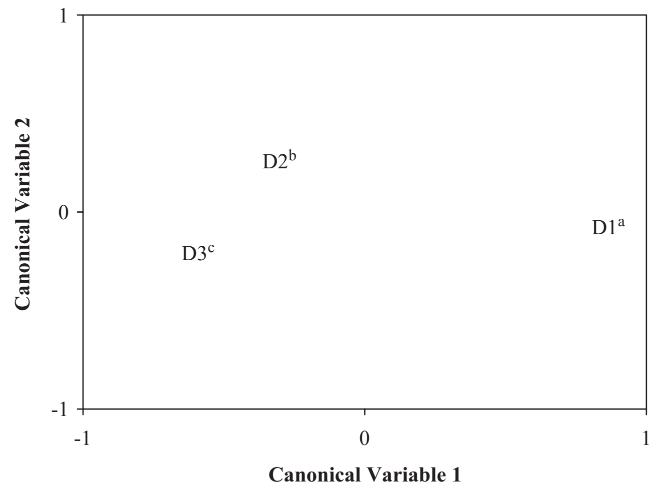


Fig. 1. Seed bank comparison at three depths using canonical discriminant analysis. Centroid means for the first and second canonical variables are plotted for each depth. Depths are signified as D1 = 0–8 cm, D2 = 8–15 cm, and D3 = 15–23 cm. Depths followed by the same letter are not significantly different at the $P \leqslant 0.05$ level.

Table 1
Inventory of weed seeds occurring[a] at three depths in a 6-year cropping system study in the semi-arid region of the Pacific Northwest, USA

| Scientific name | Common name | Soil depth (cm) | | |
|---|---|---|---|---|
| | | 0–8 | 8–15 | 15–23 |
| Winter annuals | | Percent constancy[b] in all plots | | |
| *Bromus tectorum* L. | Downy brome | 57 | 26 | 19 |
| *Sisymbrium altissimum* L. | Tumble mustard | 35 | 16 | 3 |
| *Descurainia sophia* (L.) Webb. ex Prantl | Flixweed | 32 | 12 | 6 |
| *Lactuca serriola* L. | Prickly lettuce | 14 | 3 | 4 |
| *Amsinckia* sp. | Fiddleneck | 1 | 0 | 0 |
| Summer annuals | | | | |
| *Chenopodium leptophyllum* (Moq.) Nutt. ex S.Wats | Slimleaf goosefoot | 50 | 48 | 29 |
| *Salsola tragus* L. | Russian thistle | 15 | 2 | 0 |
| *Amaranthus* sp. | Pigweed | 6 | 2 | 0 |
| *Conyza canadensis* (L.) Cronq. | Horseweed | 2 | 1 | 0 |
| *Epilobium paniculatum* Nutt. ex T. & G. | Panicle willowweed | 1 | 0 | 1 |
| *Sonchus asper* (L.) Hill | Spiny sowthistle | 1 | 0 | 0 |
| Volunteer crop | | | | |
| *Triticum aestivum* or *Hordeum vulgare* | Wheat or barley | 30 | 7 | 3 |

[a]Inventory was determined by germinating seeds screened from soil samples collected each summer.
[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.

analysis of each year showed similar results (data not shown). The major reason for discrimination based on depth appears to be related to seed density, primarily of *B. tectorum*. The 8–15 and 15–23 cm depths tended to have fewer total weed seeds than the 0–8 cm depth with the fewest at the 15–23 cm depth (data not shown). In general, when no difference existed among depths, it was because density in all three depths was low.

Table 2
Weed species factor loadings on the first and second canonical variables for sample depth. Loadings represent correlation between species count data and canonical variables.

| Species | Canonical variables | |
|---|---|---|
| | 1 | 2 |
| *Bromus tectorum* | 0.70 | −0.14 |
| *Salsola tragus* | 0.49 | −0.08 |
| *Chenopodium leptophyllum* | 0.30 | 0.85 |
| *Descurainia sophia* | 0.57 | −0.08 |
| *Lactuca serriola* | 0.37 | −0.23 |
| *Sisymbrium altissimum* | 0.59 | 0.38 |
| *P* value[a] | <0.0001 | 0.0010 |
| Variance (%)[b] | 92 | 8 |

[a]Probabilities relate to the null hypothesis that the canonical correlation for each variable is zero.
[b]Values represent the percent variance explained by each canonical variable.

### 3.2. *Bromus tectorum*

As indicated by the initial 1995 baseline sample, *B. tectorum* seed bank density in the west field site was not significantly different from zero in any of the rotations except CSW at the 0–8 cm depth (Table 3). In contrast, *B. tectorum* was more prevalent on the east field site and was greatest at the 0–8 cm depth in all rotations. Densities for the east field site ranged from 3318 to 5865 seeds $m^{-2}$ at the 0–8 cm depth compared with 0–85 seeds $m^{-2}$ on the west field site at the same depth. This difference occurred because prior to our research, the east field site had been in no-till spring barley in 1992 and 1993 and winter wheat in 1994–1995. To avoid the "green bridge" (Smiley et al., 1992) each year, the producer sprayed *B. tectorum* 1 month prior to planting no-till spring barley. However, this 1-month delay between spraying and planting allowed new *B. tectorum* to germinate and establish prior to planting the crop. Therefore, *B. tectorum* produced viable seed in barley each year. In 1994–1995, winter wheat was produced and *B. tectorum* proliferated in this system as well. The winter wheat was planted late because of drought and *B. tectorum* and winter wheat emerged

Table 3
*Bromus tectorum* seed bank response[a] to four cropping systems[b] in two adjacent field sites from 1995 through 2000 in the semi-arid winter wheat producing region of the Pacific Northwest, USA

| Year | Depth (cm) | West field site (seeds germinated $m^{-1}$) | | | | East field site (seeds germinated $m^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | WWF[c] | SWF[d] | CSW | SWSB | WWF | SWF | CSW | SWSB |
| 1995 | 0–8 | 85 f | 19 b | 37 ab | 0 a | 5206 a | 3955 a | 3318 a | 5865 a |
| | 8–15 | 16 f | 0 b | 6 bc | 6 a | 334 cd | 1180 b | 459 c | 1217 c |
| | 15–23 | 0 f | 0 b | 0 c | 6 a | 77 de | 587 bc | 453 c | 749 cd |
| 1996 | 0–8 | 1499 b | 15 b | 0 c | 0 a | 1006 b | 943 bc | 2081 b | 3383 b |
| | 8–15 | 110 ef | 15 b | 0 c | 0 a | 15 e | 0 e | 46 de | 86 e |
| | 15–23 | 15 f | 0 b | 0 c | 0 a | 0 e | 77 de | 46 de | 0 e |
| 1997 | 0–8 | 406 de | 0 b | 26 ab | 0 a | 596 bc | 557 bc | 187 cd | 448 d |
| | 8–15 | 0 f | 0 b | 0 c | 0 a | 43 de | 18 e | 48 de | 43 e |
| | 15–23 | 6 f | 6 b | 0 c | 0 a | 57 de | 18 e | 26 de | 18 e |
| 1998 | 0–8 | 1324 bc | 0 b | 0 c | 6 a | 48 de | 6 e | 26 de | 57 e |
| | 8–15 | 60 f | 0 b | 0 c | 0 a | 0 e | 0 e | 0 e | 0 e |
| | 15–23 | 6 f | 0 b | 0 c | 0 a | 0 e | 0 e | 0 e | 0 e |
| 1999 | 0–8 | 782 cd | 160 a | 6 bc | 0 a | 81 de | 392 cd | 77 de | 45 e |
| | 8–15 | 0 f | 6 b | 0 c | 10 a | 117 de | 18 e | 26 de | 0 e |
| | 15–23 | 0 f | 0 b | 18 abc | 0 a | 0 e | 6 e | 0 e | 0 e |
| 2000 | 0–8 | 5459 a | 26 b | 48 a | 6 a | 0 e | 107 de | 0 e | 0 e |
| | 8–15 | 557 d | 0 b | 0 c | 0 a | 0 e | 6 e | 0 e | 0 e |
| | 15–23 | 108 ef | 0 b | 10 abc | 0 a | 0 e | 10 e | 0 e | 0 e |

[a]Means in each column followed by the same letter are not significantly different ($P \leqslant 0.05$) based on a protected Fisher's LSD test.
[b]Crop rotations are abbreviated as follows: WWF = winter wheat/dust-mulch fallow, SWF = spring wheat/chemical fallow, CSW = continuous spring wheat, SWSB = spring wheat/spring barley.
[c]Winter wheat was grown in 1996, 1998, and 2000 on the west site and 1997 and 1999 on the east site. Alternate years were fallow on each site.
[d]Spring wheat was grown in 1996, 1998, and 2000 on the west site and 1997 and 1999 on the east site. Alternate years were chemical fallow on each site.

simultaneously. Subsequent *B. tectorum* control was poor because there was a lack of competition from the poor stand of winter wheat and ineffective in-crop herbicide control. The west field site had been in winter canola 3 years prior to this research, which reduced winter annual grass weed density.

In the west SWF, CSW, and SWSB rotations, *B. tectorum* seed density remained low throughout the study period and was generally not significantly different from zero between 1996 and 2000 at any depth (Table 3). One exception to this trend was in 1999 where 160 seeds $m^{-2}$ germinated at the 0–8 cm depth of the SWF rotation following a year of chemical fallow where herbicide applications were delayed until June allowing *B. tectorum* to produce seed. Another exception occurred in 1995, 1997, and 2000 in CSW as densities were significantly greater than zero at the 0–8 cm depth.

*B. tectorum* seed density in the west WWF rotation was greater than zero in 1996, 1998, and 2000 crop years and the 1997 and 1999 fallow years at the 0–8 cm depth (Table 3). The 1996 crop year density was greater than the 1997 fallow year density; however, there was no difference between the 1998 crop year and the 1999 fallow year densities. The 2000 crop year was greater than all previous years with a density of 5459 seeds $m^{-2}$ in 2000 (Table 3). Furthermore, density at the 8–15 cm depth was greater than zero only in 2000.

At the east field site, *B. tectorum* seed bank density was significantly less in 1996 compared with 1995 (Table 3). The WWF and SWF rotations had been in fallow since the 1995 harvest and the CSW and SWSB rotations were in spring crop in 1996; therefore, reductions in *B. tectorum* occurred as seeds germinated through the fall and winter and were killed before they could produce seed. In 1996, densities at the 8–15 and 15–23 cm depths were not significantly different from zero. In 1997, seed bank density at the 0–8 cm depth had declined in CSW and SWSB rotations from 1996, but not in WWF and SWF. From 1998 to 2000, seed bank density was not significantly different from zero in any of the four east-site rotations except for SWF in 1999. In this rotation, *B. tectorum* density increased from 6 seeds $m^{-2}$ in 1998 fallow to 392 seeds $m^{-2}$ following the 1999 spring wheat crop where an average of 3 plants $m^{-2}$ were counted in the 1999 harvest weed assessment (Young and Thorne, 2004).

### 3.3. *Chenopodium leptophyllum*

In the first 2 years of the study, *C. leptophyllum* seed bank density was low at both field sites and all three depths. In 1995, the greatest densities were found in the WWF rotation at the 8–15 cm depth but only totaled 107 and 229 seeds $m^{-2}$ in the west and east field sites, respectively (Table 4). In 1996, densities in all plots were

Table 4
*Chenopodium leptophyllum* seed bank response[a] to four cropping systems[b] in two adjacent field sites from 1995 to 2000 in the semi-arid winter wheat producing region of the Pacific Northwest, USA

| Year | Depth (cm) | West field site (seeds germinated $m^{-2}$) | | | | East field site (seeds germinated $m^{-2}$) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | WWF[c] | SWF[d] | CSW | SWSB | WWF | SWF | CSW | SWSB |
| 1995 | 0–8 | 62 bcd | 6 bc | 6 ef | 6 c | 74 de | 63 cd | 70 cd | 0 b |
| | 8–15 | 107 bc | 0 c | 0 f | 0 c | 229 cd | 29 cd | 76 cd | 9 b |
| | 15–23 | 19 cde | 6 bc | 0 f | 0 c | 6 e | 0 d | 0 d | 0 b |
| 1996 | 0–8 | 0 e | 15 bc | 0 f | 0 c | 40 de | 15 d | 68 cd | 0 b |
| | 8–15 | 0 e | 0 c | 0 f | 15 bc | 0 e | 65 cd | 0 d | 46 b |
| | 15–23 | 0 e | 15 bc | 15 c–f | 0 c | 0 e | 15 d | 24 cd | 0 b |
| 1997 | 0–8 | 18 de | 6 bc | 120 bc | 15 bc | 389 bc | 1492 a | 1065 a | 955 a |
| | 8–15 | 26 b–e | 18 bc | 77 b–e | 18 bc | 50 de | 245 bc | 523 ab | 153 b |
| | 15–23 | 6 de | 18 bc | 0 f | 10 bc | 10 e | 48 cd | 127 bcd | 147 b |
| 1998 | 0–8 | 121 b | 48 b | 102 bcd | 97 b | 838 ab | 248 bc | 130 bcd | 1347 a |
| | 8–15 | 414 a | 177 a | 1103 a | 278 a | 971 a | 646 b | 0 d | 873 a |
| | 15–23 | 122 b | 18 bc | 153 b | 26 bc | 45 de | 0 d | 0 d | 142 b |
| 1999 | 0–8 | 0 e | 0 c | 6 ef | 15 bc | 102 cde | 51 cd | 285 bc | 175 b |
| | 8–15 | 0 e | 0 c | 35 b–f | 15 bc | 39 de | 50 cd | 279 bc | 121 b |
| | 15–23 | 0 e | 0 c | 0 f | 6 c | 48 de | 43 cd | 50 cd | 6 b |
| 2000 | 0–8 | 0 e | 0 c | 0 f | 10 bc | 81 de | 26 cd | 37 cd | 18 b |
| | 8–15 | 6 de | 0 c | 10 def | 0 c | 26 e | 79 cd | 105 bcd | 37 b |
| | 15–23 | 0 e | 0 c | 0 f | 0 c | 6 e | 35 cd | 39 cd | 6 b |

[a]Means in each column followed by the same letter are not significantly different ($P \leqslant 0.05$) based on a protected Fisher's LSD test.
[b]Crop rotations are abbreviated as follows: WWF = winter wheat/dust-mulch fallow, SWF = spring wheat/chemical fallow, CSW = continuous spring wheat, SWSB = spring wheat/spring barley.
[c]Winter wheat was grown in 1996, 1998, and 2000 on the west site and 1997 and 1999 on the east site. Alternate years were fallow on each site.
[d]Spring wheat was grown in 1996, 1998, and 2000 on the west site and 1997 and 1999 on the east site. Alternate years were chemical fallow on each site.

not different from zero. However, in 1997, *C. leptophyllum* seed density increased considerably in east SWF, CSW, and SWSB assessments at the 0–8 cm depth. High densities were also found in 1998 in the east WWF and SWSB rotations at the 0–8 and 8–15 cm depths, and in all four west field site rotations at the 8–15 cm depth (Table 4). By the 2000 inventory, *C. leptophyllum* seed density was not significantly different from zero in all rotations and depths at both field sites.

### 3.4. Total seed bank density, diversity, and richness at the 0–8 cm depth

Analysis of the total weed seed bank density, diversity, and richness was limited to the 0–8 cm depth because the majority of seeds occurred at this depth (data not shown) and seeds at lower depths would not have been a factor in the no-till rotations. Total WWF weed seed density for all species at the 0–8 cm depth in 1995 was 332 and 5900 seeds m$^{-2}$ in the west and east field sites, respectively. West WWF density was lowest in 1995 and greatest in 2000, while east WWF was greatest in 1995 (Table 5). In the east SWF, CSW, and SWSB rotations, density was also greatest in 1995 and declined by 2000. A major reason for the changes in total weed seed density in these rotations was because of changes in *B. tectorum* density (Table 3). In the west SWF and SWSB rotations, density was greatest in 1999 and 1998, respectively, and reflected population peaks of broadleaf weeds, primarily *C. leptophyllum* (Table 4).

In this analysis, overall diversity was low. Shannon diversity potential was 2.5, but was never greater than 1.5 and was less than 1.0 in most assessments (Table 5). Species diversity remained relatively unchanged in the WWF rotation at both sites throughout the study (Table 5). West-site WWF diversity was greatest in 1995 and 1999, both of which were fallow years. No differences could be

Table 5
Total weed seed bank density, diversity, and species richness from the 0–8 cm soil depth[a] in four cropping systems[b] at two adjacent field sites (west and east) from 1995 to 2000 in the semi-arid winter wheat producing region of the Pacific Northwest, USA

| Year | Total density (seeds m$^{-2}$) | Shannon diversity (index)[c] | Species richness (species) | Total density (seeds m$^{-2}$) | Shannon diversity (index) | Species richness (species) |
|---|---|---|---|---|---|---|
| | | West WWF[d] | | | East WWF | |
| 1995 | 332 c | 0.6 a | 2.0 a | 5900 a | 0.3 a | 3.8 a |
| 1996 | 1800 b | 0.1 c | 1.5 a | 1293 b | 0.3 a | 1.8 bc |
| 1997 | 774 bc | 0.3 bc | 1.8 a | 1421 b | 0.9 a | 3.3 ab |
| 1998 | 1753 b | 0.3 bc | 2.8 a | 1137 b | 0.5 a | 3.0 ab |
| 1999 | 1058 bc | 0.5 ab | 3.0 a | 474 b | 1.0 a | 3.5 a |
| 2000 | 5984 a | 0.3 bc | 2.8 a | 158 b | 0.3 a | 1.3 c |
| | | West SWF[e] | | | East SWF | |
| 1995 | 67 b | 0.2 a | 1.0 bc | 4138 a | 0.1 c | 2.3 c |
| 1996 | 231 ab | 0.2 a | 1.3 bc | 1385 c | 0.5 bc | 2.0 c |
| 1997 | 47 b | 0.0 a | 0.8 c | 2795 b | 1.0 ab | 5.3 a |
| 1998 | 284 ab | 0.7 a | 2.5 a | 695 c | 1.3 a | 4.0 ab |
| 1999 | 489 a | 0.7 a | 2.5 a | 789 c | 1.0 ab | 3.5 bc |
| 2000 | 205 b | 0.5 a | 2.0 ab | 663 c | 1.1 a | 3.5 bc |
| | | West CSW | | | East CSW | |
| 1995 | 150 a | 0.2 a | 1.0 a | 3479 a | 0.2 b | 2.0 b |
| 1996 | 139 a | 0.0 a | 0.8 a | 2770 a | 0.3 b | 1.7 b |
| 1997 | 363 a | 0.4 a | 1.8 a | 2163 ab | 0.9 a | 4.5 a |
| 1998 | 363 a | 0.5 a | 2.0 a | 363 b | 1.0 a | 3.0 ab |
| 1999 | 237 a | 0.4 a | 1.8 a | 726 b | 1.0 a | 3.8 a |
| 2000 | 253 a | 0.7 a | 2.3 a | 553 b | 1.0 a | 3.3 ab |
| | | West SWSB | | | East SWSB | |
| 1995 | 33 c | 0.0 c | 0.5 b | 5961 a | 0.1 a | 2.3 c |
| 1996 | 92 c | 0.0 c | 0.5 b | 3755 b | 1.5 a | 2.3 c |
| 1997 | 158 bc | 0.3 bc | 1.0 b | 2226 c | 0.9 a | 4.5 a |
| 1998 | 616 a | 0.7 ab | 2.5 a | 2226 c | 0.9 a | 4.0 ab |
| 1999 | 316 b | 0.8 a | 2.5 a | 647 d | 1.1 a | 3.8 ab |
| 2000 | 79 c | 0.2 bc | 0.8 b | 426 d | 0.8 a | 3.0 bc |

[a]Means within a column within each rotation for each variable followed by the same letter are not significantly different ($P \leqslant 0.05$) based on a protected Fisher's LSD test.
[b]Crop rotations are abbreviated as follows: WWF = winter wheat/dust-mulch fallow, SWF = spring wheat/chemical fallow, CSW = continuous spring wheat, SWSB = spring wheat/spring barley.
[c]A maximum value of 2.5 is possible if all 12 species have equal density with at least 2 individuals per species.
[d]Winter wheat was grown in 1996, 1998, and 2000 on the west site and 1997 and 1999 on the east site. Alternate years were fallow on each site.
[e]Spring wheat was grown in 1996, 1998, and 2000 on the west site and 1997 and 1999 on the east site. Alternate years were chemical fallow on each site.

detected in the west SWF or CSW rotations, while diversity increased in both the east SWF and CSW rotations from the initial 1995 assessment (Table 5). In the west SWSB rotation, diversity was zero in the 1995 and 1996 assessments and increased to 0.8 in the 1999 assessments, and then declined in 2000, while no change was detected in the east SWSB throughout the study (Table 5).

Species richness tended to be greater in the east site than the west and reached a maximum mean of 5.3 species in the 1997 SWF (Table 5). Maximum richness in west-site rotations was 3.0 in the WWF. In the east no-till rotations, richness tended to be greatest during the middle years of the study, 1997–1999. In these rotations, *B. tectorum* was the primary weed species at the beginning of the study (Table 3), but as *B. tectorum* declined, broadleaf species composed a greater proportion of the seed bank. In the west no-till rotations, species richness was greatest in 1998 and 1999 for both SWF and SWSB, but no differences were detected in the CSW. Unlike the east site, *B. tectorum* was never a major component of the west no-till rotations, therefore, major shifts did not occur.

### 3.5. Crop rotation effect weed seed bank at the 0–8 cm depth

Canonical discriminant analysis of the weed seed bank based on crop rotation was limited to the 0–8 cm depth and only included species with 10% constancy or greater (Table 1).

In 1995, CDA segregated all east site rotations from west site rotations (Fig. 2A). Only the first canonical variable was significant in 1995 and accounted for 91% of the total variation (Table 6). *B. tectorum* was strongly correlated

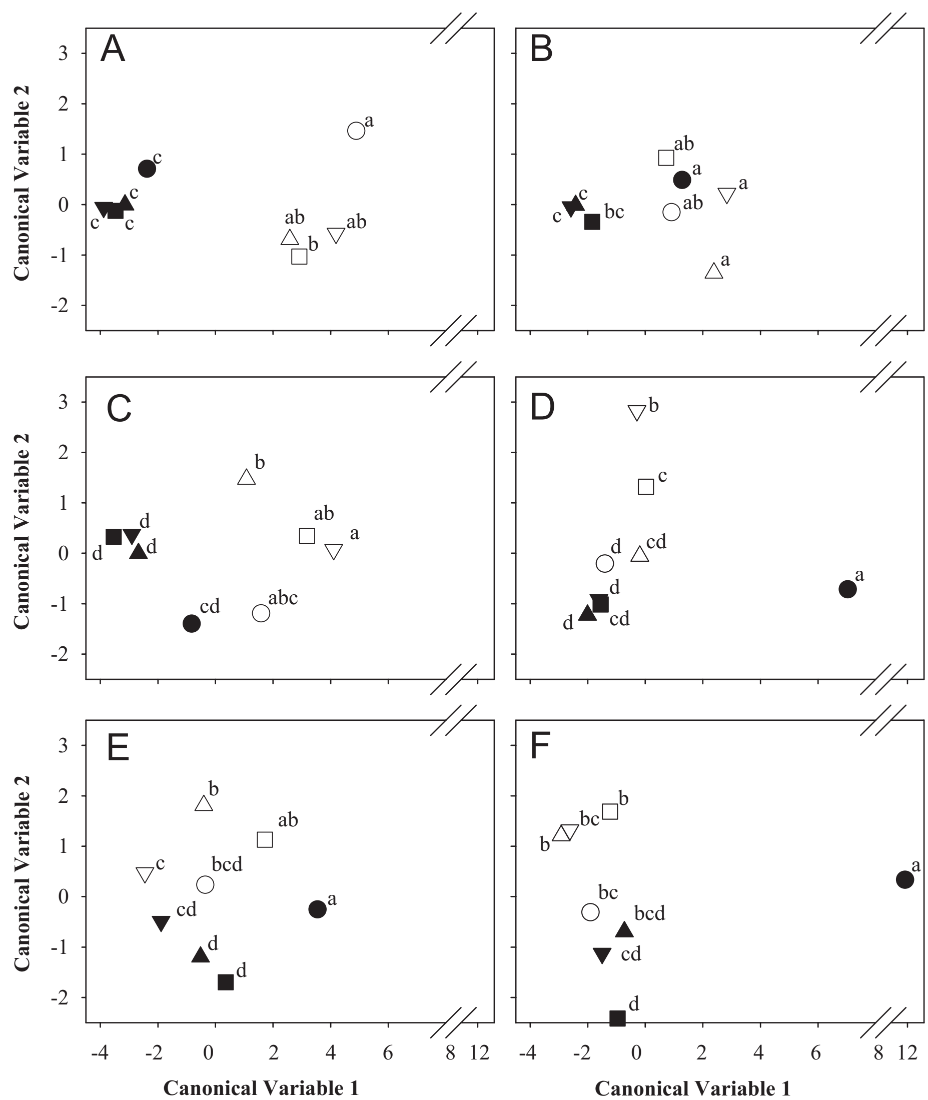


Fig. 2. (A–F) Seed bank comparison at the 0–8 cm depth using canonical discriminant analysis for the first 6 years of a cropping system study in the semi-arid region of the Pacific Northwest, USA. Figures A–F are for crop years 1995–2000, respectively. Crop rotations are represented by symbols as follows: ● = west-site winter wheat/fallow (WWF), ○ = east-site WWF, ■ = west-site spring wheat/fallow (SWF), □ = east-site SWF, ▲ = west-site continuous spring wheat (CSW), △ = east-site CSW, ▼ = west-site spring wheat/spring barley (SWSB), and ▽ = east-site SWSB. Rotations followed by the same letter are not significantly different in Mahalanobis distance at the $P \leqslant 0.05$ level.

Table 6
Weed species factor loadings on the first and second canonical variables (Can 1 and Can 2) for each year at the 0–8 cm depth. Loadings represent correlation between species count data and canonical variables

| Species[a] | Year 1995 | | Year 1996 | | Year 1997 | |
|---|---|---|---|---|---|---|
| | Can 1 | Can 2 | Can 1 | Can 2 | Can 1 | Can 2 |
| *Bromus tectorum* | 0.98 | −0.13 | 0.96 | 0.07 | 0.71 | −0.45 |
| *Salsola tragus* | 0.37 | 0.76 | 0.25 | 0.39 | 0.57 | 0.30 |
| *Chenopodium leptophyllum* | 0.27 | 0.23 | 0.18 | −0.42 | 0.67 | 0.40 |
| *Descurainia sophia* | −0.08 | 0.40 | 0.15 | 0.56 | 0.11 | 0.39 |
| *Lactuca serriola* | 0.30 | 0.11 | −0.26 | −0.03 | 0.57 | −0.09 |
| *Sisymbrium altissimum* | 0.45 | 0.24 | 0.31 | 0.43 | 0.65 | 0.54 |
| *P* value[a] | <0.0001 | 0.4662 | 0.0436 | 0.9358 | <0.0001 | 0.3680 |
| Variance[b] (%) | 91 | 4 | 84 | 8 | 85 | 8 |
| Species[a] | Year 1998 | | Year 1999 | | Year 2000 | |
| | Can 1 | Can 2 | Can 1 | Can 2 | Can 1 | Can 2 |
| *Bromus tectorum* | 0.96 | −0.07 | 0.83 | 0.16 | 0.99 | 0.11 |
| *Salsola tragus* | −0.15 | 0.46 | 0.31 | 0.15 | −0.13 | 0.29 |
| *Chenopodium leptophyllum* | −0.08 | 0.69 | −0.33 | 0.71 | −0.31 | 0.33 |
| *Descurainia sophia* | 0.18 | 0.21 | −0.19 | −0.43 | 0.30 | 0.52 |
| *Lactuca serriola* | 0.17 | 0.35 | 0.03 | −0.02 | 0.58 | −0.28 |
| *Sisymbrium altissimum* | 0.06 | 0.69 | 0.00 | 0.50 | −0.37 | 0.80 |
| *P* value[a] | <0.0001 | 0.0016 | 0.0004 | 0.0884 | <0.0001 | 0.0013 |
| Variance[b] (%) | 71 | 16 | 63 | 23 | 87 | 7 |

[a]Probabilities relate to the null hypothesis that the canonical correlation for each variable is zero.
[b]Values represent the percent variance explained by each canonical variable.

with this variable ($r = 0.98$) while *S. altissimum* ($r = 0.45$) was moderately correlated. The discrimination between east and west field sites based on the first canonical variable was corroborated by the seed bank assessment as *B. tectorum* density was considerably greater in all east field site rotations compared with the west field site (Table 3). Although the second canonical variable was not significant ($P = 0.4662$) (Table 6), the east WWF rotation was distanced higher on the second axis than the other three east rotations (Fig. 2A). This was because a few *S. tragus* seeds were found only in the east WWF plots (data not shown).

In 1996, the first crop of the study was harvested on all west field site rotations and the east CSW and SWSB rotations. The east WWF and SWF rotations had been in fallow since the 1995 crop harvest. Again, only the first canonical variable was significant and explained 84% of the variation and was strongly correlated with *B. tectorum* ($r = 0.96$) and weakly correlated with *S. altissimum* ($r = 0.31$) (Table 6). Following the first year, a transition from the initial seed bank composition was evident. The three west no-till rotations were still grouped together, but the west WWF grouped with the east field site rotations (Fig. 2B). This likely occurred because of an increase in weed seed, primarily *B. tectorum*, in the west WWF crop during the crop year, and a decrease in weed seed in the east site rotations in the fallow year. Furthermore, there was no difference in the distance between the west SWF rotation and the east WWF and SWF rotations (Fig. 2B). This would suggest the fallow period had reduced the weed seed density in these rotations as well.

The 1997 inventory followed one full rotation of the WWF and SWF systems, and the second crop of the annual crop rotations. Again, only the first canonical variable was significant, explaining 85% of the variation, and was most strongly correlated with *B. tectorum* ($r = 0.71$) (Table 6). Moderate correlations were also seen with *C. leptophyllum* ($r = 0.67$), *S. altissimum* ($r = 0.65$), *S. tragus* ($r = 0.57$), and *L. serriola* ($r = 0.57$). The west field site no-till rotations still grouped tightly together at the left of the first canonical variable, indicating low weed seed density. There was also no difference in the distance between the west and east WWF rotations (Fig. 2C). This occurred as both rotations had similar *B. tectorum* densities (Table 3); however, east WWF had greater density of *C. leptophyllum* (Table 4). The east SWSB and SWF rotation were tightly grouped at the right of the first canonical variable because of the presence of *B. tectorum* as well as the broadleaf species, primarily *C. leptophyllum* and *S. altissimum. C. leptophyllum* averaged 1492 seeds $m^{-2}$ in SWF and 955 seeds $m^{-2}$ in SWSB (Table 4), while *S. altissimum* averaged 65 and 174 seeds $m^{-2}$ in SWF and SWSB, respectively (data not shown). In contrast, the east CSW and SWSB rotations did not group together, primarily due to differences in *B. tectorum* density; east SWSB averaged 448 seeds $m^{-2}$ compared with 187 seeds $m^{-2}$ in the east CSW rotation (Table 3). Both rotations had similar populations of broadleaf species as the mean broadleaf density was 1975 and 1778 seeds $m^{-2}$

for the east CSW and SWSB, respectively (data not shown).

By 1998, major changes in seed bank dynamics were evident (Fig. 2D). The first canonical variable was again influenced mostly by *B. tectorum* ($r = 0.96$) but only accounted for 71% of the variation (Table 6). The influence of *B. tectorum* on the east no-till rotations was minimal as the plots had been out of winter wheat for 3 years. *B. tectorum* seed bank density in the east WWF rotation was also significantly reduced compared with any of the previous inventories. Furthermore, *B. tectorum* numbers were not significantly different from zero at all 3 depths in any of the no-till rotations (Table 3). In contrast, the west WWF rotation had a significant increase in *B. tectorum* seed bank density and its distance on the CDA bi-plot was significant from all other rotations on the first canonical variable axis (Fig. 2D).

The second canonical variable in the 1998 analysis was also significant and explained 16% of the variation (Table 6). Species correlating with this variable were *C. leptophyllum* ($r = 0.69$), *S. altissimum* ($r = 0.69$), and *S. tragus* ($r = 0.46$). Distribution of centroid values showed a tight grouping of the west no-till rotations and the east WWF and CSW rotations at the negative end of the second axis (Fig. 2D) indicating they all had low seed bank numbers. The east SWSB rotation was located at the positive end of the second axis and differed significantly from all other rotations while the east SWF was located mid-way on the axis. This suggests a weed shift in these two rotations, and especially the east SWSB, from *B. tectorum* to broadleaf weeds, with *C. leptophyllum* and *S. altissimum* being most prevalent. However, the seed bank increase in either of these species could not be correlated with plant density from the 1998 harvest assessment as no plants were found, and only a trace of *C. leptophyllum* (less than 1 plant $m^{-2}$) was found in 1997 (Young and Thorne, 2004). In addition, *S. altissimum* was not found in either the 1997 or 1998 assessments. This would indicate the analysis was most influenced by two factors, the decline of the once dominant *B. tectorum* and the persistence of *C. leptophyllum* and *S. altissimum* in the seed bank. However, there was no indication why the CSW rotation did not follow the same trend.

In 1999, the west site WWF and SWF rotations were in fallow and all other rotations were in crop. The first canonical variable was correlated with *B. tectorum* ($r = 0.83$), but only explained 63% of the variation (Table 6). Canonical discriminant analysis found no difference in distance between the west WWF and east SWF (Fig. 2E). An increase in *B. tectorum* in the east SWF seed bank assessment from the previous year along with a decline in the west WWF seed bank, although not significant, were likely factors in the closeness of the two rotations (Table 3). All other rotations were near zero or negative on the first axis indicating low *B. tectorum* density (Fig. 2E).

The second canonical variable was not significant at the $P \leqslant 0.05$ level, but approached significance at $P = 0.0884$ (Table 6). *C. leptophyllum* correlated more strongly ($r = 0.71$) with the second canonical variable and was found in higher numbers in the east field site rotations (Table 4), which were all positioned above zero on the second axis (Fig. 2E). In contrast, west field site rotations were all positioned below zero and had little, if any, *C. leptophyllum*. *D. sophia* correlated negatively ($r = -0.46$) with the second canonical variable and likely accounted for the negative position of the west SWF rotation (Fig. 2E). As in 1998, seed bank density could not be correlated with plant density for either of these broadleaf species. Harvest assessments in 1999 found no presence of either species (Young and Thorne, 2004).

In the 2000 seed bank assessment, the west WWF centroid value was distanced far from all other rotations on the first canonical variable (Fig. 2F). The first canonical variable was highly significant ($P < 0.0001$) and explained 87% of the variation and was strongly correlated with *B. tectorum* ($r = 0.99$) (Table 6). Seed production of *B. tectorum* in the west WWF crop strongly influenced the position of the centroid value. Seed bank density of *B. tectorum* in the west WWF had a mean value of 5459 seeds $m^{-2}$ (Table 3). This increase positively correlated with plant density from the 2000 west WWF harvest assessment ($r = 0.79$). Mean plant density for the 2000 harvest inventory was 142 plants $m^{-2}$ and was significantly greater than in previous assessments (Young and Thorne, 2004). In addition, *L. serriola* was moderately correlated ($r = 0.58$) with the first canonical variable (Table 6).

The second canonical variable was also significant ($P = 0.0013$) and explained 7% of the variation (Table 6). Unlike previous years, the species most correlated with this axis were *S. altissimum* ($r = 0.80$) and *D. sophia* ($r = 0.52$), while *C. leptophyllum* was only weakly correlated ($r = 0.33$). Furthermore, *L. serriola* had a weak negative ($r = -0.28$) correlation with the second axis. This would indicate that seed banks of the rotations aligning on the positive end of the axis contained primarily winter annual broadleaf weeds; rotations aligning on the negative end were either less weedy or reflected the presence of *L. serriola*. The east no-till rotations grouped at the positive end of the second axis but were not significantly different in distance from the east WWF and west CSW, which were positioned slightly less than zero (Fig. 2F). The east no-till rotations were positioned at the negative end of the second axis with east SWF at the most negative position. In the 2000 seed bank assessment, *L. serriola* was the only dicot weed found in east SWF, but had a relatively low density of 37 seeds $m^{-2}$ in the 0–8 cm depth (data not shown).

## 4. Discussion

Most seed bank studies in North America originate from the Midwest US or from the central Canadian provinces (Cardina et al., 2002; Buhler et al., 2001; Hoffman et al., 1998; Clements et al., 1996; Yenish et al., 1992; Gross,

1990) where a large proportion of the annual precipitation occurs during the spring and summer growing season. In these regions, the weed flora is primarily composed of summer annual grass and broadleaf weeds, which appear to be well adapted to the region's climate and cropping systems (Buhler et al., 2001; Buhler, 1999; Derksen et al., 1993; Cardina et al., 1991).

In the semi-arid winter wheat region of the Pacific Northwest, USA, most precipitation occurs during the fall and cool winter months which is followed by hot and dry summers. During our study period, 69% of the precipitation occurred between 30 September and 1 March. In this region, winter annual grass weeds, such as *B. tectorum*, are well adapted and highly competitive with winter wheat (Hulbert, 1955; Rydrych, 1974). However, when spring crops such as spring wheat or barley are planted, the warm-season broadleaf *S. tragus* can be extremely competitive (Young, 1986, 1988).

At the beginning of the study, the east field site was considerably weedier than the west site. This was reflected in the seed bank as 1995 total weed seed density at the 0–8 cm depth averaged between 3479 and 5961 $m^{-2}$ in east-site plots compared with 33–332 $m^{-2}$ in west-site plots (Table 5). In all 1995 estimates, *B. tectorum* was the predominant species. The effect of the no-till spring crop rotations on the seed bank was two-fold. First, *B. tectorum* density was dramatically reduced in the east rotations by the third crop year, and secondly, there were not any species that became a serious weed threat in the absence of *B. tectorum*. Switching to a spring crop is an effective strategy for control of this species as long as plants do not produce seed in the spring crop or chemical fallow. Rydrych (1974) found less than 2% viable *B. tectorum* seeds after 3 years in Pacific Northwest winter wheat/fallow, whereas Wicks (1997) found 1–7% survival after 1 year when seeds were deposited in August on the soil surface of stubble mulch and chemical fallow. Our results concur that viability may exceed 3 years as a few seeds did germinate in the no-till rotations at the 8–15 and 15–23 cm depths from the third crop year forward (Table 3). In no-till, it is unlikely that new seeds would have been deposited at these lower depths, unless moved downward by animals or through cracks in the soil.

A slight increase in *B. tectorum* density in the 1998 SWF assessment was apparently because plants produced seed during the chemical fallow phase. Furthermore, increases in *B. tectorum* were also noted in the west SWF and CSW in 1999 and 2000, respectively. This suggests that no-till spring cropping alone may not completely reduce the *B. tectorum* seed bank as plants escaping spring herbicide applications or those that germinate post-spray or post-plant may still produce seed. This situation exists for *Aegilops cylindrica* Host, a winter annual weed genetically similar to winter wheat and a serious problem in the western, USA. Walenta et al. (2002) reported that up to 50% of spring germinating *A. cylindrica* produce seed-bearing spikes. However, our no-till rotations were effective at reducing and maintaining low *B. tectorum* seed bank density. Furthermore, changes in the *B. tectorum* seed bank correlated well with changes in the plant population assessments (Young and Thorne, 2004), thus indicating that seed bank assessment of this species would be useful in predicting emergence within subsequent crops.

In the WWF, changes in the *B. tectorum* seed bank in both east and west field sites were solely dependent on management. Reduction of the east-site seed bank reflected efforts to keep *B. tectorum* from producing seed in the crop. These efforts included incorporation of seeds following crop harvest to enhance germination and subsequent herbicide and tillage control in the fallow year, more intense herbicide use in the crop, and pre-plant tillage in 1996 to kill seedlings that emerged following the early-fall soil-crusting rain (Young and Thorne, 2004). Concurrently, the increase in west-site seed bank density corresponded to increases in plant density within each successive winter wheat crop where management was less intense (Young and Thorne, 2004).

In contrast to *B. tectorum*, occurrence of *C. leptophyllum* did not correlate with the plant population data. Densities of less than 1 plant $m^{-2}$ were recorded in all harvest assessments (Young and Thorne, 2004); therefore, little if any seeds were added to the seed bank during this research. Therefore, germination in our seed bank assessments reflected something other than seed addition, cropping system, or crop management. Research on germination requirements for *C. leptophyllum* have not been published; however, Currie and Peeper (1988) found 0% germination in freshly matured seeds and up to 12% germination for seeds passing through harvesting equipment where mechanical injury to the seed coat broke dormancy. Research with other *Chenopodium* species would suggest that *C. leptophyllum* seeds may have long persistence in the seed bank and require exposure to light or close proximity to the soil surface, resulting from tillage, for germination (Lewis, 1973; Milberg and Andersson, 1997). It is unclear why germination was greater in 1997 and 1998 compared to other years, but it may have been climate related, as the response was not isolated to any one crop rotation.

*S. tragus* is a major weed problem in both winter and spring wheat in the semi-arid wheat region of the Pacific Northwest. During our research, *S. tragus* was present in all three population assessments during the crop year and was the focus of tillage-based weed control in the fallow phase of the WWF rotation as well as post-harvest herbicide applications in spring crop stubble (Young and Thorne, 2004). Seedlings were observed germinating under *S. tragus* skeletons as early as February during periods of above-freezing temperatures, but were killed by later frosts (personal observation). Herbicides were applied to seedlings growing in both spring and winter crops, and plants surviving through harvest were killed with herbicides following harvest. Because this species was often observed in the floristic assessments, it was expected to be more prevalent in the seed bank assessments; however it was only found in 15% of all samples at the 0–8 cm depth (Table 1). Few agricultural seed bank studies with *S. tragus* have been conducted. Ball and Miller (1989) found *S. tragus* in the seed bank of an irrigated agricultural system in Wyoming, USA using direct germination and physical extraction, which tended to overestimate the viable seed bank. Freshly matured seeds require a fall after ripening period but can germinate under a wide range of conditions in spring (Young and Evans, 1972). Allen (1982) germinated seeds that had been collected from plants and stored dry at 4 °C, while Young and Evans (1979) determined that $KNO_3$, which we used in our procedure, improves germination percentage. Furthermore, our elutriation and germination procedure did not appear to be detrimental to *S. tragus* viability. From this research, *S. tragus* appears to have a Type II transient seed bank (Thompson and Grime, 1979) where freshly matured seeds have an afterripening requirement that prevents fall germination when cold temperatures would kill newly emerged seedlings. Following the afterripening period, seeds are free to germinate whenever conditions are favorable; therefore, a long-term persistent seed bank is not maintained. Consequently, control of this species may be obtainable within only a few years by keeping plants from producing seed.

Our results differ from other seed bank studies with respect to species richness as only 11 species were found in the seed bank. In contrast, Cardina et al. (2002) found 47 species in an Ohio field, while Gross (1990) found 50 species in a Michigan field. Jansen and Jansen (1986) found more than 240 species in a semi-arid wheat/lentil *Lens culinaris* L. region of the Syrian Arab Republic. Several factors may explain the lack of diversity in our seed bank study. First, WWF has been the sole crop rotation in this region for decades with spring crops used only as a last resort when a winter wheat crop fails or for compliance with government allotment programs. Secondly, *B. tectorum* is extremely well adapted to WWF because it can germinate in the fall and winter along with the winter wheat and compete well with other weed species as well as the crop (Hulbert, 1955; Rydrych, 1974). Furthermore, herbicide control of *B. tectorum* in winter wheat is not always effective as available products usually only provide moderate control. A third factor is a general lack of warm season species, likely due to the region's climate. In spring, competition for soil moisture by winter wheat and a lack of spring and summer precipitation likely limits persistence of warm season weeds as illustrated in our study as no warm season grasses were found at any time during the research.

Our findings were similar to other seed bank research with respect to seed distribution by depth, but differed with regards to seed density in no-till systems. Previous research found weed seed distribution skewed toward the soil surface in no-till and conservation tillage cropping systems and more evenly dispersed through the tillage profile in moldboard plow systems (Hoffman et al., 1998; Yenish et al., 1992). However, Cardina et al. (2002) found weed seed density highest in no-till but no difference between chisel plow and moldboard plow systems. In our study, weed seed density was greatest near the surface in the no-till rotations as well as the WWF; however, there was no apparent increase in seed bank density with no-till. It was predicted, and shown, that *B. tectorum* density would decline in the no-till systems. Initially, *B. tectorum* was a major component of total seed bank density, especially in the east site. However, there was no corresponding increase in weed seed density or diversity by other species in response to the reduction of *B. tectorum* at the east site, or to the overall low seed bank density at the west site. This may suggest that current species in the seed bank are not potential problems for no-till in this region, but, it may also suggest there was insufficient time for current weed species to become problems or for species in other regions to fill vacant niches. The foreseeable threats are likely wind-disseminated species like *L. serriola* or *Conyza canadensis* (L.) Cronq.

## 5. Conclusions

Findings from this research suggest that no-till cropping systems in the semi-arid Pacific Northwest wheat region are effective in controlling pervasive winter annual grass weeds such as *B. tectorum* without promoting a subsequent shift to other problem species. Furthermore, with appropriate weed management, total weed seed density does not increase in no-till systems as it does in other regions where spring and summer precipitation is favorable to warm-season weeds. *Salsola tragus* does not seem to persist in the seed bank; however, additional research is needed to better understand the seed bank dynamics of this species. Long-term research is also needed to determine which species are going to be intrinsically associated with no-till cropping systems in this region.

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