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Growth and development of spring crops in competition with oat in the dryland Mediterranean climate of eastern Washington

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Abstract

Weed management during spring crop production in eastern Washington presents many challenges. Many spring crops are weak competitors with weeds. In May of 2010 and 2011, two spring crop trials were initiated near Pullman, WA, to compare the relative competitiveness of barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.), lentil (*Lens culinaris* Medik.), and pea (*Pisum sativum* L.) using cultivated oat (*Avena sativa* L.) as a surrogate for wild oat (*Avena fatua* L.) competition. The experiment was arranged as a split-block split-plot design with four replications. One set of main plots included three oat density treatments (0, 63, and 127 plants m^{-2}), while a second set included each crop species. Crop species main plots were then split into subplots of two different seeding rates (recommended and doubled). Crop populations decreased as oat density increased and increased as crop seeding rate increased. As oat density increased, preharvest crop biomass decreased for all crops, while oat biomass and yield increased. Oat biomass and yield were greater in legume plots compared with cereal plots. Increasing oat density decreased yields for all crops, whereas doubling crop seeding rate increased yields for barley and wheat in 2010 and barley in 2011. Compared with legumes, cereals were taller, produced more biomass, and were more competitive with oat.

Introduction

The Palouse region of the Intermountain Pacific Northwest (IPNW) is known for its high dryland winter wheat (*Triticum aestivum* L.) yields, averaging between 6,500 to 7,000 kg ha^{-1} (Schillinger et al. 2006). Winter wheat is typically the most profitable field crop grown in the region and is generally grown in rotation with spring crops to disrupt winter annual weed life cycles. Spring crops commonly grown in rotation include barley (*Hordeum vulgare* L.), wheat, pea (*Pisum sativum* L.), lentil (*Lens culinaris* Medik.), chickpea (*Cicer arietinum* L.), canola (*Brassica napus* L.), and condiment mustard (*Brassica* spp.) (Schillinger et al. 2006). More than 98% of the crop hectarage in the IPNW region is treated with a herbicide each year as a tool to reduce weed competition, especially in spring crops.

The IPNW climate is characterized by dry summers and wet winters. Annual rainfall ranges from 180 to 1,130 mm (Karimi et al. 2017), with most of the precipitation falling between the months of November to May. Rainfall patterns are advantageous for winter crops but are limiting for summer crops. Because moisture is a primary limitation for spring crop production, successful crop establishment and limiting competition with weeds are critical management concerns.

A major component of integrated weed management (IWM) includes a thorough understanding of crop–weed competition and requires integration of such knowledge into a comprehensive weed management plan (Swanton and Murphy 1996). Interestingly, from 1961 to 1981, only 4% of all *Weed Science* articles addressed IWM, the approach of combining direct and indirect weed control strategies into cropping systems in order to stress weed populations and increase crop competitive ability (Thill et al. 1991). A more recent article published by Young (2012) explains that the need still exists for more research to develop IWM programs.

Wild oat (*Avena fatua* L.) has been reported as one of the most serious weed problems in cereal production systems in more than 50 countries and across many cropping systems (Bell and Nalewaja 1968; Chancellor and Froud-Williams 1984; Mason et al. 2007; Scursoni and Satorre 2005; Stougaard and Xue 2005). At one time, *A. fatua* was reported to infest an estimated

11,000,000 ha in the United States, costing approximately \$1 billion annually (Chancellor and Peters 1976). Costs include tillage, reduced harvest efficiency, yield loss, reduced grain quality and added handling, and elevator and freight costs (Stougaard and Xue 2005; Wood 1953). *Avena fatua* interferes with crop production by competing for moisture, nutrients, light, and space, resulting in decreased crop growth and ultimately yields (Carlson and Hill 1985). In dryland cereal-based systems, conservation of moisture is important for long-term farming sustainability (Fuentes et. al. 2003). As competition for moisture occurs in the root zone, development of healthy and extensive crop root systems is critical (Bell and Nalewaja 1968).

Effective POST control of *A. fatua* improved substantially following the development of acetyl CoA carboxylase (ACCase)-inhibiting aryloxyphenoxypropionates and cyclohexanediones herbicide families (Heap et al. 1993). There are several effective POST herbicides for controlling *A. fatua* in cereal systems with two sites of action (ACCase and acetolactate synthase) that are available to growers today (Holm et al. 2000). In cereal systems, these herbicides have been effective in controlling or suppressing *A. fatua* populations and decreasing yield losses (Barton et al. 1992; Kirkland and O'Sullivan 1984). However, *A. fatua* remains a serious weed problem despite extensive herbicide use over the last 40 yr (O'Donovan et al. 2000). Increased resistance to herbicides that once provided effective control is the primary reason that *A. fatua* populations are increasing in some areas (Scursoni and Satorre 2005). The development of more competitive cropping systems could reduce herbicide use and minimize the negative effects of *A. fatua* competition (O'Donovan et al. 2001; Stougaard and Xue 2005). Liebman and Dyck (1993) and Liebman and Gallandt (1997) noted a demand not only for *A. fatua* integrated management approaches, but for integrated management approaches across cropping systems to diversify weed management practices.

To further evaluate IWM of *A. fatua* in the Palouse, a study was conducted near Pullman, WA, to determine the relative competitiveness of four spring crops with cultivated oat. The objective of the study was to quantify competitiveness of spring barley, wheat, lentil, and pea planted at two different densities in the Mediterranean dryland production system that occurs in the Palouse region of southeastern Washington. Parameters measured included population, crop height, leaf area index (LAI), biomass, head and pod density, yield, percent yield loss, and soil moisture.

Materials and Methods

A field trial was conducted in 2010 near Pullman, WA, at the Boyd Farm (46.751°N, 117.083°W, 808 m elevation) in an organically managed field. The same trial was repeated in 2011 at the Cook Agronomy Farm (46.780°N, 117.082°W, 808 m elevation) in a non-certified organic field. The soil type at the Boyd Farm is a Palouse silt loam (fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls) with 3.89% organic matter, pH 5.9, and a soil texture that consists of 36% sand, 54% silt, and 10% clay. The soil type at the Cook Agronomy Farm is an Athena silt loam (fine-silty, mixed, superactive, mesic Pachic Haploxerolls) with 3.5% organic matter, pH 4.8, and a soil texture that consists of 34% sand, 57% silt, and 9% clay. Residual NH_4-N was 56 kg ha^{-1} in 2010 and 21 kg ha^{-1} in 2011. Residual NH_3-N was 22 kg ha^{-1} in 2010 and 93 kg ha^{-1} (Northwest Agricultural Consultants, 2545 W. Falls Avenue, Kennewick, WA 99336). Fertility across subplots each year was assumed to be similar due to previous uniformly cropped winter pea in 2009 and winter wheat in 2010. There were no inputs or in-season tillage at either farm, with the exception of hand weeding in the control main plots. Precipitation in 2010 was 352 mm, with 79 mm falling during the trial period. Precipitation in 2011 was 422 mm, with 46 mm falling during the duration of the trial (AgWeatherNet v. 2.0, Washington Agricultural Weather Network, 24106 N. Bunn Road, Washington State University, Prosser, WA 99350).

The experiment was a split-block split-plot design with four replications. One set of main plots included three oat density treatments (0 or weed-free control, 63, and 127 plants m^{-2}) while a second set included each crop species and a cultivated oat control main plot. Crop species main plots were then split into subplots of two different seeding rates (a recommended and a doubled rate). Each replication was 21.3 by 9.8 m, each oat density main plot was 21.3 by 3.0 m, each crop species main plot was 4.3 by 3.0 m, and each subplot was 2.1 by 3.0 m. For 1X and 2X seeding rates, barley was seeded at 112 and 224 kg ha^{-1}; wheat was seeded at 123 and 245 kg ha^{-1}; lentil was seeded at 101 and 202 kg ha^{-1}; and peas were seeded at 179 and 358 kg ha^{-1}. In oat control main plots (no crop present) averaged across years, seeding rates of 65 and 259 seeds m^{-2} resulted in established populations of 63 and 127 plants m^{-2}, respectively. Crop cultivars were selected based on disease resistance, competitiveness, and adaptation to the region. 'Bob', a two-rowed feed barley, was planted in 2010 and 2011 (Ullrich et al. 2003). 'Louise', a common soft white spring wheat variety, was planted in 2010, and 'Kelse', a hard red spring wheat, in 2011 (Kidwell et al. 2006, 2009). 'Riveland', a large-seeded, yellow-cotyledon lentil variety, was planted in 2010, and 'Brewer', a small black-seeded line was planted in 2011 (McPhee and Muehlbauer 2009; Muehlbauer 1987). 'Supra', a marrowfat dry pea, was planted in 2010, and 'Aragorn', a smooth round green dry pea, was planted in 2011. A tall, white-kernel, late-maturing, cultivated variety of oat 'Park' was used in 2010 and 2011 to simulate *A. fatua*. Cultivated oat was used in this experiment to minimize shattering, which allowed for all plants to be harvested simultaneously to accurately record both crop and oat yields.

All crops and oats were planted on May 13, 2010, and on May 25, 2011, with a 2.2-m-wide ten-opener Fabro double disk drill with 19-cm row spacing (Fabro Enterprises, P.O. Box 517, Swift Current, SK S9H 3W3, Canada). Due to excessive moisture, the timing of spring crop plantings in this trial were relatively late compared with typical planting dates in the Pullman, WA area, which often occurs as early as mid-March, weather permitting.

Crop response measurements included crop, oat, and other weed biomass besides oat (excluding oat biomass), cereal head and legume pod density, crop and oat yield, percent yield loss, and percent soil moisture. Crop population, height, and LAI were measured in time in 2010 at approximately 2-wk intervals. In 2011, measurement intervals were based on those of the 2010 trial accumulated growing degree days (AGDDs). If the measurement interval was not precisely the same, AGDDs were averaged across years to combine and compare measurements. The largest variance in averaged AGDDs was 273 growing degree days (GDDs). The following formula with a T_{base} of 2.2 C was used to calculate daily GDDs. $T_{\max}$ and $T_{\min}$ temperatures were retrieved from AgWeatherNet.

$$\mathrm{GDD} = \frac{T_{\max} - T_{\min}}{2} - T_{\text{base}}$$

Crop population was measured at 244, 376, 515, and 690 AGDDs, which was approximately weekly. Total oat and crop plants were counted and averaged for each subplot over three random 0.25-m row lengths. Three random crop and oat plant heights were measured and averaged for each subplot at 945, 1,049, 1,459, and 1,716 AGDDs.

LAI was measured four times throughout the growing season in all weed-free main plots at 805, 1,049, 1,459, 1,716 AGDDs. LAI is a dimensionless value, where values range from 0 to 9, with 0 representing bare ground and 9 representing a dense canopy. LAI was automatically calculated from above- and below-canopy measurements taken by an AccuPAR Ceptometer (Decagon Devices, 2365 NE Hopkins Court, Pullman, WA 99163). The AccuPAR Ceptometer determines LAI after the user has identified zenith angle, fractional beam, and leaf distribution parameters. Zenith angle, the angle the sun makes with respect to a line vertical to the location on the earth's surface where observations are occurring, was automatically calculated from user entry of latitude, longitude, and time of day. Fractional beam is the amount of diffuse and direct beam radiation reaching the canopy and is retrieved by taking an LAI measurement over bare ground while the user covers the sensor on the probe (sensor 80) that only measures diffuse radiation (Decagon 2003). A parameter of 1 was used for the leaf distribution parameter, which indicates that the canopies had a spherical-shaped distribution (Decagon 2003).

For all aboveground plant material determinations, two 0.10-m^2 quadrats were harvested to determine biomass from each subplot before harvest. Samples were separated by crop, oat, and other weed species. Samples were dried at 60 C for 3 d before being weighed. Cereal heads and legume crop pods were counted from each 0.10-m^2 quadrat. Subplots were harvested on August 31, 2010, and on September 12, 2011, with a Kincaid XP-8 Plot Combine (Kincaid Equipment Manufacturing, P.O. Box 400, Haven, KS 67543) modified for small plot use. Weed seed was initially cleaned from all samples by using a No. 10 U.S.A Standard Testing Sieve (Fisher Scientific, 300 Industry Drive, Pittsburgh, PA 15275). Samples were then cleaned using a seed blower that was fashioned from a 757 South Dakota Seed Blower (Seedburo Equipment, 2293 S. Mt Prospect Road, Des Plaines, IL 60018) with a 10.16-cm tube and removable cup. If necessary, lentil and pea samples were additionally cleaned with a No. A Seedburo Dockage Sieve (Seedburo Equipment). Cleaned seed was then weighed to determine crop yield per subplot as well as oat yield per subplot, an indicator of the potential seed rain of *A. fatua*. For barley and wheat, yield was determined by subsampling harvested grain samples and separating crop and oat seed by hand.

Test weight was determined according to Approved Method 55-10 (AACC International 2010). Kernel weight, kernel diameter, hardness index, and moisture content were evaluated using a Single Kernel Characterization System (SKCS) Model 4100 (Perten Instruments, P.O. Box 9006 SE-126 09, Hägersten, Sweden). Wheat protein was determined by near-infrared spectroscopy according to Approved Method 39-10 (AACC International 2011) with a Perten Inframatic 9200 Grain Analyzer (Perten Instruments). Barley protein was not determined, because barley feed quality is only assessed by other characteristics, such as test weight, and damaged kernels (USDA 1997).

Soil was sampled at 2 wk after harvest for percent moisture content. No precipitation was recorded during the 2-wk interval either year. Two 1.5-m cores were taken from each subplot and divided into five sections; 0 to 10, 10 to 30, 30 to 61, 61 to 91, 91 to 122, and 122 to 152 cm. Corresponding sections from each subplot were then homogenized. Soil moisture percentage was determined by calculating the difference between wet and dry weights of each sample.

A univariate analysis was performed on all responses to test for stable variance (SAS v. 9.4; SAS Institute, SAS Campus Drive, Cary, NC 27513). Data sets for crop height, crop biomass, oat biomass, weed biomass, and cereal head and legume pod density were natural log transformed, which stabilized variance. A value of one was added to crop biomass, oat biomass, weed biomass, and cereal head and legume pod density values before applying the natural log transformation to the data. Adding a value of one to the values of each data set was necessary in order to include values of zero in the natural log transformation analysis. Crop population, LAI, crop and oat yield, percent yield loss of crops, percent soil moisture, test weight, kernel weight, kernel diameter, hardness index, moisture content, and wheat protein content responses were not transformed, as transformation did not increase stabilization.

A mixed model was then used to determine the effects of oat density, crop species, crop seeding rate, and the interactions among the three effects on crop biomass, oat biomass, weed biomass, cereal head and legume pod density, yield of both crop and oat yield, percent yield loss of crops, and percent soil moisture (SAS v. 9.4; SAS Institute). A repeated statement was added to the mixed model to determine the effects of AGDDs, oat density, crop species, crop seeding rate, and the interactions among the four effects for measurements that were assessed over time (crop population, height, and LAI). The main effect of AGDDs was not discussed, because significance was assumed. However, significant interactions with AGDDs were explained. For responses excluding LAI, biomass measurements, and oat yield, significant differences are only described between cereals (barley and wheat) and between legumes (lentil and pea), due to the obvious differences that exist between the two types of crops.

For grain quality, transformation did not increase stabilization, so all responses were left nontransformed. A mixed model was then used to determine the fixed effects of oat density and crop seeding rate on test weight, kernel weight, kernel diameter, hardness index, moisture content, and wheat protein content. Random effects included year and replication. For cereal grain quality, barley and wheat were not directly compared, due to their differences in U.S. grade standards. Additionally, wheat quality responses from 2010 and 2011 were not compared, due to the fact that a common soft white spring variety was used in 2010 and a hard red spring variety in 2011.

Results and Discussion

Crop population, crop biomass, oat biomass, weed biomass, head/pod density, oat yield, crop percent yield loss, soil moisture, grain moisture, kernel weight, moisture, and protein were averaged over year due to no significant year effect ($P \leq 0.05$). Crop height, LAI, crop yield, test weight, kernel diameter, and wheat hardness index were analyzed by year, as year was significant for these parameters.

Crop Population

Averaged over year, an AGDD by crop species interaction, oat density main effect, and seeding rate main effect were significant for crop population ($P < 0.0001$, $P = 0.0009$, and $P = 0.0012$, respectively). From 244 to 376 AGDDs, all cereal and legume populations increased. Cereal populations began to decrease by 515 AGDDs, while legume populations became asymptotic at 690 AGDDs. A lack of recruitment in legume populations suggests that seeding rates were not high enough to encourage intraspecific competition (Table 1).

Table 1. Populations (plants m^{-1} row) for barley, wheat, lentil, and peas in response to an accumulated growing degree day (AGDD) by crop species interaction and oat density and crop species main effects at Pullman, WA, in 2010 and 2011.[a]

Factor	Crop population			
AGDD by crop species	Barley	Wheat	Lentil	Pea
	————	——plants m^{-1} row——		————
244	29 fg	40 b	21 h	6 i
376	40 b	50 a	40 bc	19 h
515	33 de	39 bc	35 cd	20 h
690	27 g	31 d-g	32 ef	19 h
Oat density				
—plants m^{-2}—				
0		33 a		
63		29 b		
127		28 b		
Seeding rate[b]				
1X		25 b		
2X		35 a		

[a] Means within a column for each factor followed by a common letter were similar according to Fisher's protected LSD at $P < 0.05$.

[b] For 1X and 2X seeding rates, barley was seeded at 112 and 224 kg ha^{-1}; wheat was seeded at 123 and 245 kg ha^{-1}; lentil was seeded at 101 and 202 kg ha^{-1}; pea was seeded at 179 and 358 kg ha^{-1}.

At 690 AGDDs, wheat populations (31 plants m^{-1} row) were similar to barley (27 plants m^{-1} row) and lentil (32 plants m^{-1} row), while pea populations were less (19 plants m^{-1} row). As oat density increased from 0 to 63 and from 0 to 127 oat plants m^{-2}, all crop populations decreased on average by 4.5 plants m^{-1}. Additionally, as crop seeding rate increased from the 1X to 2X rate, all crop populations increased by 10 plants m^{-1} row (Table 1).

Many studies have explained that as crop population increases, weed biomass and other measures of weed abundance decrease (Bell and Nalewaja 1968; Korres and Froud-Williams 2002; Mason et al. 2007; Mohler 1996; O'Donovan et al. 1999, 2000; Radford et al. 1980; Scursoni and Satorre 2005; Stougaard and Xue 2005). Conversely, as weed density increases, the same phenomenon is observed for measures of crop growth and productivity. We observed similar trends, as crop populations increased as crop seeding rate increased and decreased as oat density increased. When considering all crop populations, wheat populations were greater than all other crop populations, barley populations were greater than the legume populations, and lentil populations were greater than pea populations (Table 1).

Crop Height

An oat density by crop seeding rate interaction and crop main effect were significant for crop height in 2010 ($P = 0.0050$ and $P < 0.0001$, respectively). At the 1X seeding rate, crops were 3-cm taller in weed-free main plots compared with plots with 63 oat plants m^{-2} present. Crop heights at the 2X rate also were approximately 2-cm taller than crop heights at the 1X rate in main plots with 63 and 127 oat plants m^{-2} present. Cereal crop heights were greater than legume crop heights by approximately 42 cm. Barley was taller than wheat, pea, and lentil by 14, 47, and 51 cm, respectively, and pea and lentil were similar (data not shown). A crop species main effect was significant in 2011 for crop height ($P < 0.0001$). Barley was taller than wheat, pea, and lentil by 10, 30, and 42 cm, respectively. Wheat was taller than the legumes by approximately 26 cm, and pea was taller than lentil by 12 cm (data not shown).

Previous studies have determined that height is an important factor in competitive ability (Champion et al. 1998; Cosser et al. 1997; Hucl 1998; Huel and Hucl 1996; Korres and Froud-Williams 2002; Lemerle et al. 2001). However, height is often a more important competitive trait in cereal systems than in row-cropping systems (Appleby et al. 1976; Balyan et al. 1991; Challaiah et al. 1986; Garrity et al. 1992; Hucl 1998; Lemerle et al. 1996; Seefeldt et al. 1999). In this study, the cereal crops were taller than the legume crops, and barley was taller than wheat. After biomass and crop and oat yield were assessed, taller crops were found to produce the most biomass and had the highest yields, suggesting that height likely contributed to competitive ability in this study. However, other plant traits in association with height, such as early emergence and vigor, early canopy closure, light interception, biomass accumulation, and ground cover, also are important and contribute to the ability of a variety to suppress and/or tolerate weeds (Champion et al. 1998; Huel and Hucl 1996; Mason et al. 2007).

LAI

Crop species and crop seeding rate were significant main effects for LAI in 2010 ($P = 0.0067$ and $P = 0.0148$, respectively). Barley LAI was greater than legume LAI, while wheat and lentil were similar, and lentil and pea were similar. All crop LAI values increased when seeding rate was doubled (data not shown). In 2011, an AGDD by crop species interaction and crop seeding rate main effect were significant for LAI ($P < 0.0001$ and $P = 0.0123$, respectively). At 805 and 1,040 AGDDs, pea had a greater LAI than all other crops; however, by 1,459 AGDDs, all crop LAI values were similar and remained similar at 1,716 AGDDs. An increase in seeding rate increased LAI values for all crops (data not shown).

LAI values in 2010 correlated positively with competitive crops when considering other parameters assessed in this study (crop biomass and crop and oat yield); however, values in 2011 did not. Huel and Hucl (1996) and Jennings and Aquino (1968) also observed that LAI did not appear to have an association with competitiveness. However, other leaf parameters in combination with traits such as leaf length, orientation, and canopy diameter have been documented to be associated with crop competitive ability (Challaiah et al. 1986; Huel and Hucl 1996).

Crop, Oat, and Weed Biomass (g m^{-2})

Oat density and crop species affected preharvest crop biomass ($P = 0.0035$ and $P < 0.0001$, respectively). Crop biomass in weed-free main plots was 1.7 times greater than crop biomass in plots with 63 oat plants m^{-2} present and 2.5 times greater than crop biomass in plots with 127 oat plants m^{-2} present. Crop biomass was similar in plots with 63 and 127 oat plants m^{-2} present. Preharvest barley and wheat biomass was similar across treatments, while barley biomass was 4.5 times greater than lentil biomass and 4 times greater than pea biomass. Wheat biomass was 3.9 times greater than lentil biomass and 3.5 times greater than pea biomass. Lentil and pea biomass were similar (Table 2).

Averaged across years, a crop species by crop seeding rate interaction and oat density main effect were significant for oat biomass ($P = 0.0179$ and $P = 0.0086$, respectively). In barley subplots, an increase in crop seeding rate decreased oat biomass by 2.6 times. Oat biomass in barley subplots planted at the 2X rate was also less than oat biomass in wheat, lentil, and pea subplots, regardless of the rate they were planted at. Oat biomass in 2X wheat subplots was approximately 1.4 times less than oat biomass in both lentil

Table 2. Crop biomass (g m^{-2}) in response to oat density and crop species, oat biomass in response to oat density and a crop species by seeding rate interaction, and other biomass in response to oat density at Pullman, WA, in 2010 and 2011.

Factor	Biomass[a]						
Oat density	Crop			Oat			Other[b]
—plants m^{-2}—	—g m^{-2}—						
0	642 a			–			–
63	368 b			271 b			60 a
127	256 c			545 a			25 b
Crop species							
Barley	718 a			–			–
Wheat	631 a			–			–
Lentil	180 b			–			–
Pea	160 b			–			–
Crop species by seeding rate[c]		Barley	Wheat		Lentil	Pea	
1X	–	307 c	298 cd		491 a-c	600 a	–
2X	–	116 d	376 bc		528 ab	544 ab	–

[a] Biomass was collected before seed harvest of all crops and oat. Means within a column for each factor followed by a common letter were similar according to Fisher's protected LSD at $P < 0.05$.

[b] Other weed biomass besides oat.

[c] For 1X and 2X seeding rates, barley was seeded at 112 and 224 kg ha^{-1}; wheat was seeded at 123 and 245 kg ha^{-1}; lentil was seeded at 101 and 202 kg ha^{-1}; pea was seeded at 179 and 358 kg ha^{-1}.

Table 3. Cereal head and legume pod densities (no. m^{-2}) and oat yield (kg ha^{-1}) in response to oat density and crop species in Pullman, WA, in 2010 and 2011.[a]

Factor	Head/pod density	Oat yield	2010 yield				2011 yield				Yield loss
Oat density	—no. m^{-2}—	—kg ha^{-1}—									—%—
—plants m^{-2}—											
0	652 a	–		1,967 a				1,455 a			0 b
63	371 b	885 b		1,327 b				753 b			56 a
127	219 c	1,666 a		956 b				586 b			65 a
Crop species											
Barley	493 b	641 b		–				–			29 c
Wheat	53 c	843 b		–				–			31 c
Lentil	762 a	18,008 a		–				–			44 b
Pea	73 d	1,810 a		–				–			58 a
Crop species by seeding rate[b]			B	W	L	P	B	W	L	P	
1X	–	–	2,909 b	2,122 d	112 e	49 e	1,552 b	1,478 b	171 c	77 c	–
2X	–	–	3,559 a	2,430 c	109 e	42 e	2,437 a	1,415 b	234 c	86 c	–

[a] Means within a column for each factor followed by a common letter were similar according to Fisher's protected LSD at $P < 0.05$.

[b] Abbreviations: B, barley; W, wheat; L, lentil; P, pea.For 1X and 2X seeding rates, barley was seeded at 112 and 224 kg ha^{-1}; wheat was seeded at 123 and 245 kg ha^{-1}; lentil were seeded at 101 and 202 kg ha^{-1}; peas were seeded at 179 and 358 kg ha^{-1}.

1X and 2X subplots. Oat biomass in wheat 2X subplots was 1.3 and 1.4 times less than oat biomass in 1X and 2X pea subplots, respectively (Table 2). For other weed biomass (weeds other than oats), oat density was significant, averaged across years ($P = 0.0319$). Other weed biomass in main plots with 63 oat plants m^{-2} present was 2.4 times higher than in main plots with 127 oat plants m^{-2} present (Table 2).

Averaged over years, oat density and crop species significantly affected cereal head and legume pod densities ($P = 0.0004$ and $P < 0.0001$, respectively). From 0 to 63 oat plants m^{-2}, from 0 to 127 oat plants m^{-2}, and from 63 to 127 oat plants m^{-2}, cereal heads and legume pods per square meter decreased by 1.8, 3.0, and 1.7 times, respectively. Barley and wheat head densities were similar; however, lentils produced 10 times more pods than peas did (Table 3).

Gaudet and Keddy (1988) explained the relationship between plant traits and competitive ability by assessing 44 wetland species. Their results indicated that plant biomass explained 63% of the variation in competitive ability, while plant height, canopy diameter, canopy area, and leaf shape explained most of the residual variation. Biomass also was a critical plant trait measured in our experiment, especially as the study took place in a dryland cropping system where available moisture was limited. Productivity of a given area of land in a dryland system is primarily limited by available moisture. When crops are growing in competition with weeds, if the crop does not utilize the available moisture, the weeds are likely to.

As oat density increased so did its biomass, causing a corresponding decrease in crop biomass. Barley and wheat produced more biomass than oat, regardless of seeding rate, while legume crop biomass was consistently lower than oat biomass. Scursoni and Satorre (2005) reported similar decreases in barley biomass as oat density increased; however, they also found that barley biomass was not affected by oat density when barley was planted at its highest seeding rate, 280 plants m^{-2}. Kirkland (1993) observed fresh weight reductions of 30% and 46% in wheat (6-leaf stage) when oat populations were 64 and 118 plants m^{-2}, respectively, and Stougaard and Xue (2004) documented wheat biomass decreased by 55% as oat density increased.

An increase in crop seeding rate did not significantly increase crop biomass in this study, but other studies have documented otherwise. Radford et al. (1980) found that there were increases in wheat biomass and decreases in *A. fatua* biomass when wheat density increased up to 150 plants m^{-2}. When wheat densities were lower than 150 plants m^{-2}, *A. fatua* caused greater losses to wheat biomass. Stougaard and Xue (2004) observed that spring wheat biomass decreased as *A. fatua* density increased; however, the magnitude of wheat biomass reduction varied by crop seeding rate. Low spring wheat seeding rate treatments (175 plants m^{-2}) had a more rapid reduction in biomass compared with high spring wheat seeding rate treatments (280 plants m^{-2}).

Crop Yield

In 2010, an oat density main effect and a crop species by seeding rate interaction were significant for crop yield ($P = 0.0034$ and $P = 0.0092$, respectively). All weed-free crop yields (1,967 kg ha^{-1}) were 1.5 times greater than crop yields in main plots with 63 oat plants m^{-2} present (1,327 kg ha^{-1}) and were 2.1 times greater than crop yields in main plots with 127 oat plants m^{-2} present (956 kg ha^{-1}). Barley yields (3,234 kg ha^{-1}) were 1.4 times greater than wheat yields (2,276 kg ha^{-1}) across treatments, while lentil and pea yields were less than cereal yields and were similar (data not shown). Additionally, as crop seeding rates doubled, cereal yields increased by approximately 1.2 times, while legume yields were not affected by an increase in seeding rate (Table 3).

In 2011, an oat density main effect and a crop species by seeding rate interaction were significant for crop yield ($P = 0.0025$ and $P = 0.0046$, respectively). All weed-free crop yields (1,455 kg ha^{-1}) were 1.9 times greater than crop yields in main plots with 63 oat plants m^{-2} present (753 kg ha^{-1}) and were 2.5 times greater than crop yields in main plots with 127 oat plants m^{-2} present (586 kg ha^{-1}). Across treatments, barley yields (1,995 kg ha^{-1}) were 1.4 times greater than wheat yields (1,447 kg ha^{-1}), while lentil and pea yields were similar, 203 and 81 kg ha^{-1}. Additionally, as crop seeding rates doubled, barley yields increased by approximately 1.6 times, while yields of all other crops were not affected by an increase in seeding rate (Table 3).

Oat Yield

Averaged over years, oat density and crop species were significant for oat grain yield ($P = 0.0010$ and $P = 0.0006$, respectively). Oat yields in main plots with 127 oat plants m^{-2} present (1,666 kg ha^{-1}) were 1.9 times greater than yields in plots with 63 oat plants m^{-2} present (885 kg ha^{-1}). Oat yields in barley and wheat subplots were similar; however, oat yields in lentil and pea subplots (1,808 and 1,810 kg ha^{-1}, respectively) were 2.8 times greater than oat yields in barley subplots (710 kg ha^{-1}) and 2.1 times greater than oat yields in wheat subplots (843 kg ha^{-1}), respectively (Table 3).

The effect of crop species on oat yield in both years suggests that crop type plays an important role in suppressing oat yields and the potential of *A. fatua* seed rain. Cereal crops were more suppressive of oat seed rain potentials than legume crops, and barley was more suppressive than all other crops. An increase in crop seeding rate did not contribute to suppression of oat seed rain potentials.

Crop Percent Yield Loss

Averaged over years, oat rate and crop species were significant main effects for crop percent yield loss ($P < 0.0001$ and $P < 0.0001$, respectively). Compared with weed-free main plots, percent yield losses for all crops averaged 56% when 63 oat plants m^{-2} were present and 65% when 127 oat plants m^{-2} were present. Barley and wheat yield losses were similar, while legume yield losses were greater than cereal yield losses, and percent yield loss for pea subplots was 14% more compared with lentil subplots (Table 3).

In a study conducted by Young et al. (1994), average *A. fatua* populations northwest of Pullman, WA, at the time of winter wheat harvest were 30 plants m^{-2} in areas that were managed at a high weed management level, while areas that were managed at a low weed management level were 120 plants m^{-2}. Barley (160 plants m^{-2}) yield losses of 40% were reported by Morishita and Thill (1988) when 170 *A. fatua* plants m^{-2} were present. Wilson and Peters (1982) reported 72% yield losses in barley crops with 662 *A. fatua* seedlings m^{-2}, and Chancellor and Peters (1976) reported barley losses of 30% to 50% when *A. fatua* densities were more than 100 plants m^{-2}. Stougaard and Xue (2005) reported decreases in spring wheat yields by 54% as *A. fatua* densities increased from weed-free plots to plots planted to 80, 155, and 285 *A. fatua* plants m^{-2}.

An increase in crop yield due to increased seeding rates has been observed in other studies. Ball et al. (1997) and Boerboom and Young (1995) reported increased yields in lentil due to increased crop seeding rates; however, responses varied depending on treatments, years, cultivars, locations, and experiments. Increased pea yields as a result of increased crop seeding rate also have been reported by Townley-Smith and Wright (1994) and Boerboom and Young (1995).

Percent Soil Moisture

Averaged over year, oat rate, crop species, and soil depth were significant for percent soil moisture ($P = 0.0001$, $P = 0.0039$, and $P < 0.0001$, respectively). Weed-free plots had approximately 1.5% more moisture than plots with both 63 and 127 oat plants m^{-2} present. Percent soil moisture in lentil and pea plots was similar (12.2%), while percent moisture in barley and wheat plots also was similar but was 0.9% less than in legume plots. Soil depth also had an effect on percent soil moisture, with moisture increasing as depth increased (data not shown).

Compared with lentil and pea, barley and wheat were taller, produced more biomass, and were more competitive with oat. Barley and wheat yields were greatest in weed-free conditions and decreased in the presence of oats. Lentil and pea yields also decreased when oats were present compared with when they were not, but were overall low due to a delayed spring planting. An increase in crop seeding rate increased all crop populations, height, and LAI. A crop species by seeding rate interaction also was present for oat biomass and crop yield in 2010 and 2011, with an increase in seeding rate decreasing oat biomass. A doubling in seeding rate also increased cereal yields in 2010 and barley yield in 2011. Crop seeding rate did not considerably affect crop biomass, weed biomass, cereal head and legume pod densities, oat yield, or percent yield loss.

Grain-quality responses were affected by oat density and crop seeding rate in only a few instances. Increased oat density decreased kernel weights in 2011 for barley and wheat. Doubled crop seeding rates decreased barley and wheat test weights in 2010 as well as hardness index values in 2011 (data not shown). However, the magnitudes of these effects were small when considering grading standards. Therefore, growers wishing to use increased wheat and barley seeding rates to provide additional competition with weeds may not need to be overly concerned about effects on grain quality.

When considering biomass production and crop and oat yields, spring barley and wheat were strong competitors against oat compared with lentil and pea. Crop selection also may increase the suppression of weed seed rain potentials. In this study, cereal crops were more suppressive of oat seed rain potentials than legumes. Similar studies also have found barley to be more competitive than wheat (Cousens 1996; Dew 1972; Fisher et al. 2000; O'Donovan et al. 1985; Pavlychenko and Harrington 1934) and grass crops more competitive than legume crops (Baraibar et al. 2018).

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