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Camelina: Adaptation and performance of genotypes

Stephen O. Guy[a,*], Donald J. Wysocki[b], William F. Schillinger[c], Thomas G. Chastain[d], Russell S. Karow[d], Kim Garland-Campbell[e], Ian C. Burke[a]

[a] *Department of Crop and Soil Sciences, Washington State University, Pullman, WA 99164, USA*
[b] *Department of Crop and Soil Science, Oregon State University, Columbia Basin Agricultural Research Center, Pendleton, OR 97801, USA*
[c] *Department of Crop and Soil Sciences, Washington State University, Dryland Research Station, Lind, WA 99341, USA*
[d] *Department of Crop and Soil Science, Oregon State University, Corvallis, OR 97331, USA*
[e] *USDA-ARS, Wheat Genetics, Quality, Physiology, and Disease Research Unit, Washington State University, Pullman, WA 99164, USA*

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ABSTRACT

Camelina (*Camelina sativa* L. Crantz) has shown potential as an alternative and biofuel crop in cereal-based cropping systems. Our study investigated the adaption, performance, and yield stability among camelina genotypes across diverse US Pacific Northwest (PNW) environments. Seven named camelina genotypes and 11 experimental numbered genotypes were evaluated for seed and oil yield in trials at 18 location/year environments that spanned four annual precipitation zones. Locations were rainfed with long-term mean annual precipitation ranging from 242 to 1085 mm. Thirteen trials were spring-planted and five were fall-planted. Oil content was determined on seed from seven trials, seed weight from five trials, plant height and grain density from four trials, and plant lodging from two trials. Yield stability index was determined and related to seed yield across trials and within each of four annual precipitation zones. Seed yields varied from a trial mean of 127 kg/ha at Lind WA during a year of extreme drought to 3302 kg/ha at Pullman WA with the grand mean 1213 kg/ha. Seed yields among genotypes were significantly different ($P < 0.05$) in 10 environments and ranged across environments from 913 kg/ha for 'GP07' to 1349 kg/ha for 'Celine'. Spring planting produced higher yields than fall planting and named genotypes out-performed numbered genotypes overall. Between the two highest yielding genotypes, 'Calena' was more stable for yield than Celine. Stability index values varied among genotypes within each annual precipitation zone evaluated indicating adaptation differences among genotypes. Oil content varied from 29.6% to 36.8% across environments but varied less among genotypes – 30.8–32.9%. Oil content was negatively correlated to seed yield. Grand means for camelina performance characteristics in four trials were 1.25 g/1000 seed weight, 92.4 cm plant height, and 652 kg/m^3 seed density. Named genotypes were more productive than numbered genotypes across environments and can be grown is diversified environments when selected based on anticipated precipitation, seed yield, oil content, and other agronomic characteristics.

1. Introduction

Camelina, a cool-season member of the Mustard family, is native to central Asia and the Mediterranean and is also referred to as gold-of-pleasure or false flax (McVay and Lamb, 2008; McVay and Kahn, 2011). Camelina is mostly grown as an annual spring-planted crop with 85–100 days from emergence to maturity, but there are fall-planted cultivars that overwinter as rosettes. Plants grow to 1.0 m height under favorable conditions and produce small cream colored flowers terminally on branched stems. Flowers are predominately self-pollinated. Twelve to 18 seeds are produced in teardrop shaped pods 5–6 mm in diameter. Pods of commercial cultivars typically have only minor shattering, but open reliably during threshing. Seeds are small, even by Mustard family standards, at 800,000 seeds kg^{-1}, about 30% the weight of *Brassica napus* canola seed (Gugel and Falk, 2006).

Camelina was a commonly grown crop in Europe until the middle-ages when importance of the crop declined, but has been grown more widely in recent decades (Zubr, 1997; Gugel and Falk, 2006). Interest in low-input oilseed crops for biofuel production, recently described by Shonnard et al. (2010), has created widespread consideration of camelina as a potential crop, especially in the Pacific Northwest (PNW) region of the United States, because there is limited oilseed acreage in the region. Recent introduction of camelina in North America has expanded to 8100 planted hectares in the northern Great Plains in 2011 (NASS, 2012), but there has been only minor production to date in the inland PNW.

* Corresponding author. Tel.: +1 509 335 5831; fax: +1 509 335 8674.
E-mail address: sguy@wsu.edu (S.O. Guy).

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Camelina should be adapted to the dryland PNW because it is considered to be more cold, heat, and drought tolerant, and less susceptible to disease and insects than canola (*Brassica napus* L.) and the grain legume crops that are currently grown in the region (Schillinger et al., 2012; Wysocki et al., 2013; Henderson et al., 2004). Schillinger et al. (2012) reported water use efficiency of 2.8 kg seed/ha/mm across four dryland PNW locations with diverse precipitation. This water use efficiency demonstrates the adaptation of camelina to the PNW climate, but was determined on only one cultivar. The rainfed cropping area of the inland PNW is quite diverse, receiving from 150- to 650-mm average annual precipitation whereas the Willamette Valley, situated between the Cascade mountains and the Coast mountain ranges, receives more than 1000 mm of annual precipitation (Peel et al., 2007). Currently, low market price for seed, limited agronomic knowledge, and cultivars with unknown adaptation contribute to grower reluctance to produce camelina.

Genetic refinement of camelina for adaptation in North America has been limited compared to canola. There are commercial camelina breeding efforts underway in North America and in Austria (Vollmann et al., 2007) where selection has emphasized genetic improvements in seed yield, seed size, oil content, and oil composition. Field studies in Austria evaluating 30 genotypes showed yields up to 2250 kg/ha and oil content from 40.6 to 46.7% averaged across three environments, although seed size and oil content were determined to be negatively correlated (Vollmann et al., 2007). Across 10 PNW planting dates at four locations, yield at the optimum planting date varied from 130 to 2900 kg/ha, showing great variability and also the potential for camelina production when properly sown (Schillinger et al., 2012). Because of the diversity of environments and potential for camelina in the PNW, genotypic adaptation will be an important factor for future commercial production (Hulbert et al., 2012). Information on genotypic variation for seed yield, oil content, and other agronomic characteristics of camelina in Washington, Oregon, and Idaho has not been previously reported. The objective of this three-year study was to investigate the seed yield, oil content, and general adaption of camelina genotypes in field trials across four diverse temperature and precipitation zones.

2. Materials and methods

2.1. Locations

Studies were conducted to evaluate seed yield and oil content of 18 camelina genotypes at six sites during three years (18 location-years or environments) in the PNW, specifically: Lind, WA, Lewiston, ID, Pendleton, OR, Pullman, WA, Moscow, ID, and Corvallis, OR. Located in the Columbia Plateau region between the Cascade and Bitterroot mountain ranges, Lind is the driest environment with moderate temperatures, Lewiston and Pendleton are intermediate in precipitation and warmer, and the Moscow and Pullman sites are the wettest and coolest with the exception of Corvallis. Corvallis has high precipitation and mild temperatures and is located in the Willamette Valley west of the Cascade mountain range. The cool-Mediterranean-type climate at these locations typically has late autumn through spring dominate precipitation and dry, warm summers. Rainfed production is predominant at all locations and average annual precipitation is 242 mm at Lind, 324 mm at Lewiston, 418 mm at Pendleton, 534 mm at Pullman, 695 mm at Moscow, and 1085 mm at Corvallis. Precipitation was measured in all locations at nearby official U.S. National Weather Service recording sites (Table 1).

Thirteen trials were spring-planted and five fall-planted, although dates varied widely within fall and spring planting times (Table 2). Planting was done as early as sites could be prepared in the spring and at later fall times that favor camelina (Schillinger et al., 2012). Soil textures are silt loams ranging from coarse silt loam at Lind to silty clay loam at Corvallis, are well drained and more than 150 cm in depth. The four major rainfed agricultural production zones in the PNW, defined by Schillinger et al. (2006), are represented by the study locations. Study sites were on university experiment farms, except the Lewiston site which was located in a cooperator grower's field.

2.2. Overview of experiment

Eighteen camelina genotypes were evaluated at all 18 environments (Table 2) in randomized complete block, four replication experiments with unique randomization for each trial. Genotypes consisted of seven named genotypes and 11 numbered genotypes still under development. The numbered genotypes with a 'GP' prefix were obtained from Dwayne Johnson, formerly with Montana State University, and later with Great Plains Oil and Exploration, LLC, Cincinnati, OH. The numbered genotypes with a 'SO' prefix were obtained from Fernando Guillen-Portal with Sustainable Oils, LLC, Bozeman, MT. Origins of all genotypes are listed in Table 3. Seed used in all trials was distributed from a single seed stock source maintained at Pullman, WA.

Five experiments were paired for comparison of fall- and spring-planted trials in 2009 and 2010 at Lind and Pendleton, and in 2009 at Corvallis. Other paired trials were fall-planted in 2009 but were abandoned due to unusually cold and wet conditions coupled with excessive slug damage at Corvallis and weed infestation at Pullman. All spring-planted trials were successfully completed. Fall planting difficulties support the advantage for spring planting reported by Schillinger et al. (2012). Planting was conducted in mid-to-late fall and spring dates were as early as soil conditions allowed. Planting rate was 5.6 kg seed/ha. Nitrogen fertilizer was applied to all sites at moderate rates based on soil test. Averaged over the three years, nitrogen application rates at Lind, Pendleton, Moscow-Pullman-Lewiston, and Corvallis were 28, 45, 78, and 68 kg/ha, respectively. Weeds were controlled prior to planting with glyphosate [N-(phosphonomethyl)glycine] and in-crop grass weeds were controlled by either Poast™ (sethoxydim) or Assure II™ (quizalofoz-p-ethyl). All trials were planted following other crops in rotation rather than after summer fallow, although a summer fallow rotation is the customary practice in areas with less than 350 mm annual precipitation (Table 2). Trials at Lind WA were direct seeded into standing wheat stubble with a hoe-opener equipped drill. Other locations were planted using drills with double-disk openers after customary tillage practices to prepare a seedbed. Further details on fall and spring tillage and planting methods used in the experiment are reported by Schillinger et al. (2012). Row spacing in all locations was 15 cm. Plot dimensions were 2.5 × 30 m at Lind; 1.5 × 6.1 m at Lewiston, Pendleton, Pullman, and Moscow; and 3 × 15 m at Corvallis.

2.3. Measurements

Seed was harvested using plot combines when camelina plants had turned golden-brown and seed moisture was below 9%. Combines were equipped with lower screens having 3 mm round or square holes, or 3 mm × 15 mm slotted holes to enhance seed and pod separation. Harvested areas were 46.5 m^2 at Lind; 9.2 m^2 at Lewiston, Pendleton, Pullman, and Moscow; and 23 m^2 at Corvallis. Oil contents of individual plot yield samples were measured from seven trials. Oil content was determined gravimetrically on 350 g seed samples by mechanical oil extraction using a seed press (Monforts Komet CA59G). Oil and seed meal were collected over a two-minute period and percent oil was calculated based on the

Table 1
Crop-year (Sept. 1–Aug. 31) precipitation (mm) at six sites during the 3-year study.

Month	Lind			Pendleton			Lewiston	Pullman		Moscow	Corvallis		
	2008	2009	2010	2008	2009	2010	2008	2009	2010	2008	2008	2009	2010
Sept.	4	0	4	7	3	0	3	8	2	23	44	22	30
Oct.	17	6	39	33	5	45	27	8	53	64	110	38	75
Nov.	28	20	21	53	39	46	42	85	45	97	110	120	207
Dec.	30	38	32	60	71	44	9	95	35	133	240	153	138
Jan.	41	22	36	45	52	43	19	87	47	78	221	94	172
Feb.	6	23	21	16	35	18	11	35	31	38	68	84	111
Mar.	21	45	19	56	65	35	19	92	29	60	114	97	154
Apr.	5	23	30	13	45	71	14	55	66	27	61	33	111
May	3	21	47	33	36	100	24	55	53	38	10	93	84
June	12	6	35	34	29	73	18	18	63	46	26	16	70
July	0	3	8	3	0	0	6	22	13	7	1	20	3
Aug.	7	8	2	15	35	5	21	27	0	51	31	6	13
Total	174	215	294	368	416	479	213	587	437	662	1036	776	1168

Table 2
Location, year, and planting dates for 18-year/location/planting season environments.

Location[a]	Crop-year	Planted season	Planting date	Previous crop
Lind	2008	Spring	6 Mar. 2008	w. wheat
Lind	2009	Fall	19 Nov. 2008	w. wheat
Lind	2009	Spring	27 Feb. 2009	w. wheat
Lind	2010	Fall	21 Oct. 2009	w. wheat
Lind	2010	Spring	1 Mar. 2010	w. wheat
Pendleton	2008	Spring	12 Mar. 2008	w. wheat
Pendleton	2009	Fall	20 Nov. 2008	w. wheat
Pendleton	2009	Spring	18 Mar. 2009	w. wheat
Pendleton	2010	Fall	19 Oct. 2009	w. wheat
Pendleton	2010	Spring	4 Apr. 2010	w. wheat
Lewiston	2008	Spring	3 Apr. 2008	w. wheat
Pullman	2009	Spring	8 Apr. 2009	w. wheat
Pullman	2010	Spring	3 Mar. 2010	w. wheat
Moscow	2008	Spring	26 Apr. 2008	s. barley
Corvallis	2008	Spring	12 Apr. 2008	perennial ryegrass
Corvallis	2009	Fall	5 Dec. 2008	w. wheat
Corvallis	2009	Spring	13 Mar. 2009	w. wheat
Corvallis	2010	Spring	19 Feb. 2010	oat

[a] Location/year/planting season are components of the 18 environments where 18 camelina genotypes were experimentally evaluated.

Table 3
Camelina seed yield and yield range across 18 environments, yield between five fall and spring planted environments, oil content in seven environments, and seed weight in five environments in the Pacific Northwest from 2008 to 2010.

Genotypes	Source[a]	Seed yield		Seed yield		Seed oil[d] %	1000 seed weight[e] (g)
		Mean (kg/ha)	Range[b] (kg/ha)	Fall planted[c] (kg/ha)	Spring planted[c] (kg/ha)		
Blaine Creek	MSU	1224	100–3150	986	1198**	31.7	1.181
Calena	Europe	1344	146–3469	1094	1120	32.0	1.271
Celine	Europe	1349	163–3795	1022	1103	32.1	1.258
Columbia	GP Oil	1226	119–3432	795	1075***	32.6	1.150
Cheyenne	Blue Sun	1188	118–3258	896	1054*	32.1	1.243
Ligena	Europe	1259	106–3395	952	1131**	32.9	1.406
Suneson	MSU	1209	159–3481	830	1061**	32.5	1.186
SO-1	Sus. Oil	1233	147–3166	965	1115*	32.8	1.196
SO-2	Sus. Oil	1205	126–3294	798	1122***	32.2	1.291
SO-3	Sus. Oil	1184	126–3137	880	1104**	31.8	1.220
SO-4	Sus. Oil	1213	130–3287	827	1103***	31.5	1.181
SO-5	Sus. Oil	1234	171–3603	807	1168***	32.5	1.273
SO-6	Sus. Oil	1112	130–3371	778	960**	31.9	1.207
GP07	GP Oil	913	131–2785	476	879***	31.9	1.461
GP41	GP Oil	1242	165–3623	869	1166**	32.2	1.276
GP42	GP Oil	1230	64–3113	900	1159***	32.3	1.256
GP48	GP Oil	1230	72–3341	827	1133***	30.8	1.251
GP67	GP Oil	1209	124–3253	975	1102	32.2	1.197
Average		1213	128–3331	871	1097***	32.1	1.250
LSD (0.05)		70		131	131	0.6	0.034

[a] Seed sources: Montana State University (MSU), Great Plains Oil & Exploration, LLC (GP Oil), Blue Sun Energy, Inc. (Blue Sun), Sustainable Oils, LLC (Sus. Oil).
[b] Range values are among environments.
[c] Data are the average of five fall and the corresponding five spring trials: Pendleton and Lind, 209 and 2010; and Corvallis 2009.
[d] Data from seven trials: Moscow 2008, Pullman 2009 and 2010, Pendleton 2010 fall, Lind 2010 fall and spring, and Corvallis 2010.
[e] Data from five trials: Pullman 2010 and Corvallis 2008–2010.
*, **, ***Significant at the 0.05, 0.01, 0.001 levels, respectively, between fall and spring planted yields.

Table 4
Location, year, planted in spring (S) or fall (F), seed yield, seed yield range across genotypes, comparison between named cultivars and numbered lines, difference between fall and spring planted, and oil yields for 18 locations of camelina trials in the Pacific Northwest.

Location	Crop year	Seed yield			Named vs. Numbered[b]	Δ Fall vs. spring[c] (kg/ha)	Oil yield (kg/ha)
	Planting timing F = fall, S = spring	Mean (kg/ha)	Range[a] (kg/ha)	*P* value	*P* value		
Lind	2008-S	127	64–170	0.7894	ns		
Lind	2009-F	579	455–695	0.1298	ns	−49 ns	
Lind	2009-S	530	380–660	0.0944	ns		
Lind	2010-F	1001	615–1315	0.1368	0.204	156***	297
Lind	2010-S	1157	855–1315	0.4788	ns		364
Pendleton	2008-S	1707	1250–1710	0.0011	ns		
Pendleton	2009-F	1051	630–1280	0.0561	0.001+	589***	
Pendleton	2009-S	1640	1145–1760	0.0001	0.079+		
Pendleton	2010-F	730	270–1000	0.0021	0.013+	898***	242
Pendleton	2010-S	1628	1280–2245	0.0756	ns		
Moscow	2008-S	1303	1090–1415	0.0074	0.587		395
Pullman	2009-S	3302	2785–3795	0.0199	0.059+		977
Pullman	2010-S	2965	2210–3255	0.0002	0.001+		998
Lewiston	2008-S	832	530–1100	0.0271	0.068+		
Corvallis	2008-S	253	164–340	0.1649	0.116		
Corvallis	2009-F	994	355–1420	0.0001	0.041+	−62***	
Corvallis	2009-S	532	380–690	0.0051	ns		
Corvallis	2010-S	1478	995–1975	0.0001	0.001+		544
Mean		1213	913–1350	0.0001		227***	545

[a] Range values are among genotypes.
[b] (+) indicates a seed yield advantage for named versus numbered genotypes.
[c] (−) indicates a seed yield advantage for fall versus spring planted paired trials.
*** Significant at the 0.001 level.

total weight of the oil and seed meal. Verification of oil extraction by nuclear magnetic resonance oil analysis shows greater than 98% extraction efficiency using this press and methods. The oil yield was computed based on seed yield and oil percentage.

Seed weight was determined in five trials by weighing 2000 counted seeds. Immediately before harvest in four trials, plant height was measured from ground level to the top raceme and lodging was rated immediately before harvest as a percentage of lodged plants. Grain density was determined in four trials by weighing grain in a standard volume 0.946 L test weight cup. Eberhart and Russell (1966) stability index (SI) was calculated to evaluate the yield variability across environments.

2.4. Statistical analyses

Data from individual years and combined over environments were analyzed using ANOVA and means separated using Fischer's protected least significant difference at $P < 0.05$ unless otherwise noted (MSTAT, 1990). The effect of fall versus spring planting was analyzed by paired comparison. Environment and replication were treated as random effects and genotype was treated as a fixed effect. Comparison of named and numbered genotypes was by orthogonal comparison. Pearson correlations were calculated in MSTAT. Eberhart and Russell (1966) stability index (SI) was calculated to evaluate the yield variability across all environments and across environments within precipitation zones. Least squares means were calculated for each genotype within each environment and for each environment across all genotypes using Mixed models analysis in SAS. The REG procedure of SAS was then used to regress the genotype mean within each environment on the environmental means. From this analysis, an estimate of the regression slope and R^2 value was used to assess the stability of each camelina genotype evaluated in this study as described in Eberhart and Russell (1966). Then the Eberhart and Russell stability index (SI) was plotted against mean seed yield across environments and within precipitation regions to further compare performance among genotypes and potential variability due to environmental differences.

3. Results and discussion

3.1. Seed yield

3.1.1. Seed yield – environments

Seed yields varied widely among environments from a mean of 127 kg/ha at Lind spring planted during extreme drought in 2008–3302 kg/ha at Pullman spring planted in 2009 (Table 4). The grand mean yield across environments and genotypes was 1213 kg/ha. Much of the variation among environments is related to precipitation, especially for the low precipitation environments such as Lind that received only 174 mm of precipitation for the 2008 crop year (Sept. 1–Aug. 31). In 2009 and 2010 at Lind, precipitation was 215 mm and 294 mm, respectively, with spring planted mean yields of 520 and 1157 kg/ha, respectively. This shows the response of camelina to available water, but also the risk to production if precipitation is below normal.

There were other yield limiting factors. At Lewiston in 2008, birds damaged the trial before harvest as evidenced by broken racemes and scattered seed and pods on the soil surface. At Moscow, yields from spring planting in 2008 were limited by delayed planting. At Corvallis, humidity and high precipitation fostered infestation of downy mildew *Hyaloperonospora camelinae* (Putnam et al., 2009) in 2009 and 2010 and predation by slugs. Schillinger et al. (2012) and Wysocki et al. (2013) also showed that camelina is not well-adapted to the Willamette Valley of western Oregon.

Yields among genotypes varied within each environment and were significantly different from each other ($P < 0.05$) in ten environments. Genotype means showed probability of differences from 0.05 to 0.10 in three environments, and there were no differences in five environments (Table 4). At Lind, the site with the least precipitation, the lowest probability of differences among genotypes was 0.094. The percentage difference between the range of yield values was least at Moscow spring 2008 (30%) followed by Pullman spring 2009 (36%) and Pendleton spring 2008 (37%); while the greatest differences were at Pendleton fall 2010 (270%) and Corvallis fall 2009 (300%), and all had significant differences

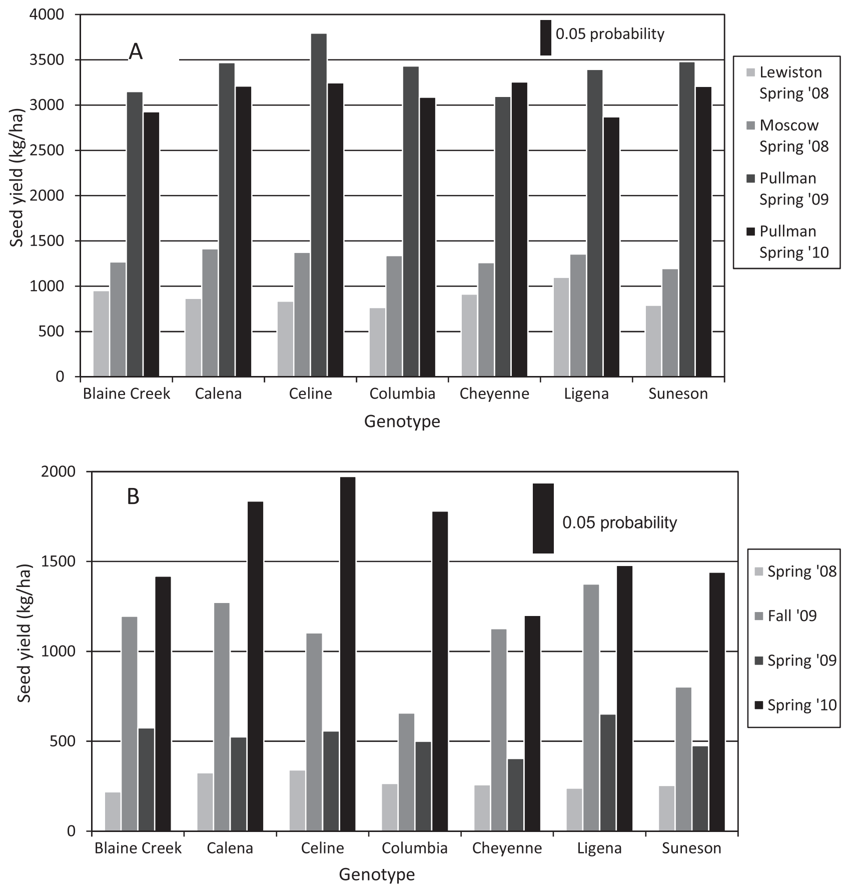

Fig. 1. Seed yield of seven named camelina cultivars evaluated three years in the Pacific Northwest in 8 environments: A: four in the Palouse and B: four at Corvallis. Bars indicate significant difference at the 0.05 probability level among varieties within an environment.

among genotypes. The mean yield values across genotypes varied by 47% (Table 3). Orthogonal contrasts between fall- and spring-planted locations showed higher mean seed yield when spring-planted at Lind in 2010, 156 kg/ha, although there was no difference found between fall- and spring-planted at Lind in 2009, and at Pendleton, 898 and 589 kg/ha between fall- and spring-planted in 2010 and 2009, respectively (Table 4). However, at Corvallis in 2009, fall-planted camelina out-yielded spring-planted by 462 kg/ha on average. The grand mean showed a highly significant ($P < 0.001$) yield increase with spring- versus fall-planted camelina (Table 3). These results are consistent with planting date experiments reported by Schillinger et al. (2012).

3.1.2. *Seed yield – genotypes*

Mean seed yield among genotypes compared across environments ranged from 913 kg/ha for 'GP07' to 1349 kg/ha for 'Celine' (Table 3). Yields of Celine and 'Calena', 1349 and 1344 kg/ha, respectively, were significantly higher than all other genotypes. The entries GP07 and 'SO-6' were significantly lower yielding than all other genotypes, and the other 14 entries were not different among themselves except 'Ligena' yielded more than 'SO-3'. Yield range did not always follow average yields. Minimum yield for all genotypes occurred at Lind in spring 2008 with no differences among genotypes in that trial. The maximum yield for each genotype was recorded in either Pullman spring 2009 or 2010. In both environments there were significant differences among genotypes. Seed yields for all genotypes averaged across the five fall-planted environments were lower than those averaged across the five corresponding spring locations and were significantly different for 15 genotypes. The average yield for the paired fall- and spring-planted environments was 871 and 1097 kg/ha, again showing a consistent advantage to spring planting. Both Celine and Calena, the two highest yielding entries, were not significantly different between fall and spring planting, indicating more consistent performance among environments. Calena was also found to be most consistent for yield among nine genotypes in the Maritime Provinces of Canada; an environment very different than the PNW (Urbaniak et al., 2007).

3.1.3. *Seed yield – genotypes × environments*

Orthogonal contrasts between seven named genotypes and 11 numbered genotypes showed an advantage for seed yield of the named genotypes in eight environments ($P < 0.001–0.080$) (Table 4). For the environments where there was no significant difference between named and numbered genotypes, there were generally no differences among genotypes (exceptions are Pendleton spring 2008, Moscow spring 2008, and Corvallis spring 2009). Because of the yield advantage evident in named genotypes, combined analyses were conducted among environments within a region for performance. The analysis showed a significant genotype × environment interaction for the Palouse and Corvallis regions, but not for Pendleton and Lind. This was expected for Lind because there were no significant differences within any trial in that region.

Yields of named genotypes are presented in Fig. 1 for Palouse and Corvallis regions. The interaction of genotype × environment was significant despite no differences among named genotypes in the spring 2008 trials at Lewiston and Moscow. The interaction was significant because Celine was highest yielding in Pullman in 2009 but not different from most other cultivars in 2010 (Fig. 1A).

'Cheyenne' was the only entry that yielded more in 2010 than 2009. There were no yield differences among named cultivars at Corvallis in spring 2008 and spring 2009. However, fall 2009 and spring 2010 trials at Corvallis had very different yield responses among named genotypes and accounts for the significant genotype × environment interaction (Fig. 1B). Yield of 'Columbia' was lowest of all named genotypes in fall 2009 but was the same as the highest yielding named genotypes Celine and Calena in spring 2010. Cheyenne and Ligena were not different between fall 2009 and spring 2010, but all other cultivars were different, Celine and 'Suneson' produced nearly doubled yield between fall 2009 and spring 2010, and Columbia showed nearly triple yield. These significant interactions, especially under high yield potential conditions, show that genotype selection can be an important management decision for successful camelina production. Perplexing is the potential for year-to-year variation in relative performance of genotypes that can make cultivar selection less precise and such variation persists across regions as shown in this manuscript.

3.1.4. Seed yield – stability

To further evaluate the yield variation for the 18 genotypes across environments, seed yield among all 18 environments was plotted against Eberhart and Russell (1966) Stability Index (SI) (Fig. 2). Using this evaluation, the most desirable genotypes are high yielding and are stable across environments, deviating least from SI values of 1. The goodness of fit of each genotype varied in this analysis from $r^2 = 0.992$ to 0.940, showing high confidence. The genotype GP07 was not only lowest yielding, but also the most variable. The highest yielding were Celine and Calena, but Celine showed a more deviant SI. It fit better in some environments than Calena, but not as well in others. This difference in stability is supported by the greater yield range across environments by Celine than by Calena (Table 3). The next highest yielding genotype, Ligena, was less variable as were most other genotypes.

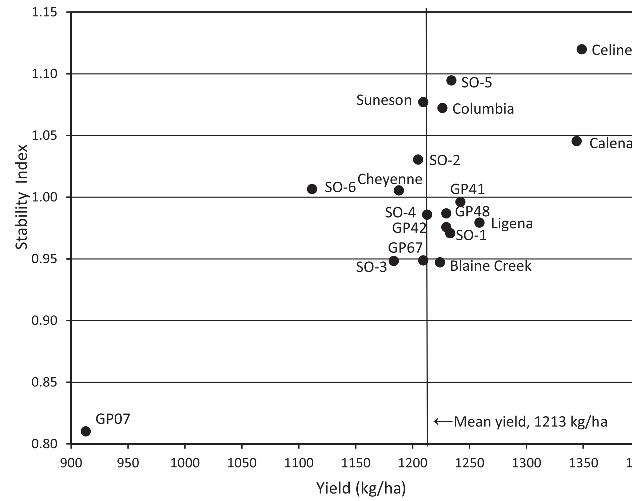

Fig. 2. Classification of seven named camelina genotypes and 11 numbered genotypes evaluated in 18 rainfed environments in the Pacific Northwest from 2008 to 2010 based on mean seed yield and stability index.

To evaluate yield and SI within precipitation environments of the PNW, the SI was calculated among the five Lind trials (low precipitation), six Pendleton and Lewiston trials (intermediate precipitation), three Moscow and Pullman trials (moderately-high

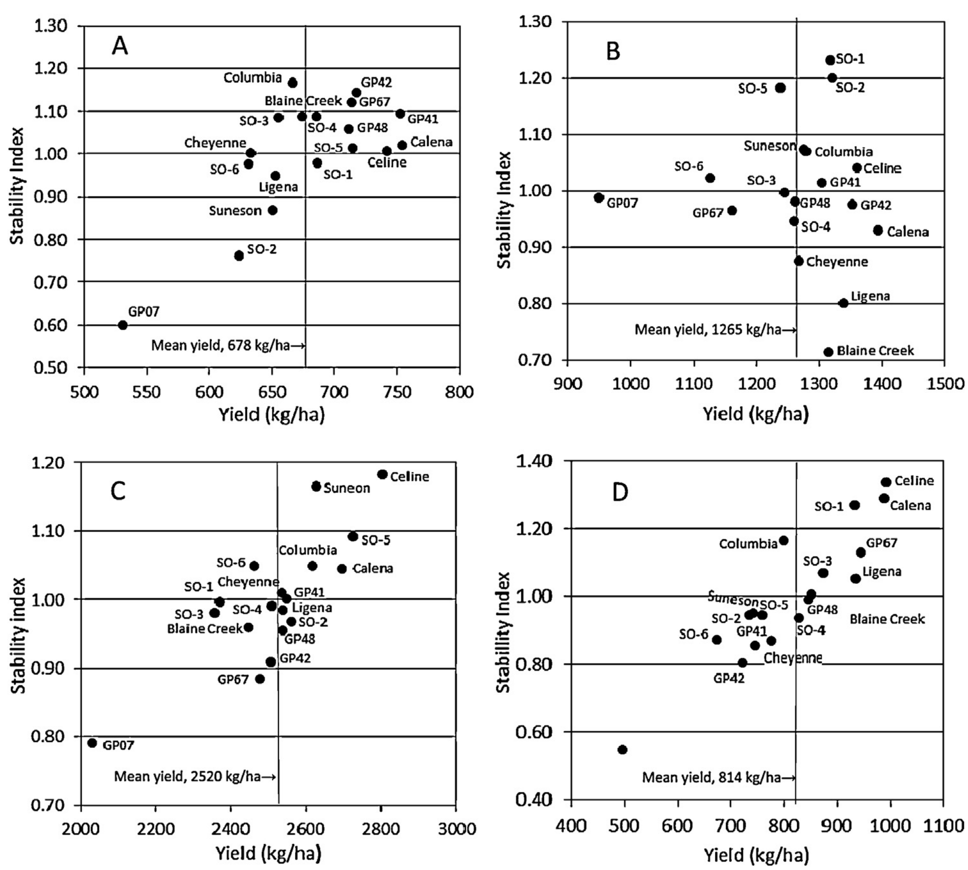

Fig. 3. Classification of seven named camelina genotypes and 11 numbered genotypes evaluated in different environments: A: Lind, B: Pendleton, C: Pullman and Moscow, and D: Corvallis, across three years in the Pacific Northwest from 2008 to 2010 based on mean seed yield and stability index.

Table 5
Oil content and range across genotypes, and Pearson correlations between seed yield and oil content from seven Pacific Northwest trials across 18 genotypes of camelina.

Location	Crop year	Oil content		Correlation yield vs. oil
	Planting timing F = fall, S = spring	Mean (%)	Range (%)	r^2
Lind	2010-F	29.7	28.8–31.2	0.254*
Lind	2010-S	31.5	30.3–33.0*	−0.291*
Pendleton	2010-F	33.2	31.5–34.9	−0.283*
Moscow	2008-S	30.3	29.8–31.4***	0.167
Pullman	2009-S	29.6	28.1–30.9**	−0.018
Pullman	2010-S	33.7	30.6–36.1***	−0.770***
Corvallis	2010-S	36.8	35.1–38.5***	0.113
Mean		32.1	30.8–32.9***	−0.216***

* Significant at 0.05 level.
** Significant at 0.01 level.
*** Significant at 0.001 level.

Table 6
Camelina plant heights, lodging, seed yield, grain density, and oil content for 18 genotypes at four rainfed environments in northern Idaho and eastern Washington from 2008 to 2010.

Genotypes	Plant height (cm)	Lodging[a] (%)	Seed yield (kg/ha)	Grain density (kg/m^3)	Seed oil content[b] (%)
Blaine Creek	91.1	11	1847	650	31.9
Calena	91.4	10	1994	647	31.1
Celine	94.3	9	2059	657	31.1
Columbia	91.0	9	1919	664	31.8
Cheyenne	91.9	10	1898	636	31.1
Ligena	93.4	16	1942	643	32.5
Suneson	94.6	18	1931	661	31.3
SO-1	87.6	6	1791	648	32.0
SO-2	93.3	15	1886	664	31.4
SO-3	92.9	14	1727	649	31.1
SO-4	87.3	24	1882	651	30.6
SO-5	95.1	6	1952	656	31.5
SO-6	91.9	15	1804	642	30.8
GP07	80.3	21	1529	657	30.9
GP41	95.4	21	1904	661	31.4
GP42	95.1	20	1886	666	31.1
GP48	97.7	36	1921	655	29.5
GP67	97.2	21	1774	651	31.0
Average	92.4	16	1869	652	31.2
LSD (0.05)	4.8	14	160	13	0.7

[a] Lodging occurred only at the two Pullman locations.
[b] Seed oil content data for Pullman 2009 and 2010, and Lewiston 2008.

precipitation), and four Corvallis trials (high precipitation) (Fig. 3). An SI of '1' indicates that a genotype has average response to more favorable environmental conditions, while SI values below '1' indicate that genotypes do not respond well to more favorable environments (Eberhart and Russell, 1966). The SI comparison for Lind camelina yields also showed that GP07 had the lowest SI, but most genotypes grouped from 0.9 to 1.2 (Fig. 3A). Both Calena and Celine had SI values close to 1.0 and were the two highest yielding named cultivars. The Pendleton and Lewiston SI analysis (r^2 = 0.857–0.989) showed 'Blaine Creek' with the lowest, SI = 0.71, and 'SO-1' the highest, SI = 1.23 (Fig. 3B). Again the two highest yielding entries, Calena and Celine, were close to SI = 1. The SI values at Pendleton and Lewiston did not tend to increase with increasing yield as was found in the two higher precipitation environments. The Pullman and Moscow environment had the narrowest SI range (Fig. 3C) with Celine having highest and GP07 lowest SI values. The range of fit to the model (r^2 = 0.913–0.999) was the closest for any environment. Genotypes at Corvallis had the greatest range of SI values compared to other locations with GP07 at 0.54 and Celine at 1.34, and the greatest range of fit to the model (r^2 = 0.758–0.999) for any environment (Fig. 3D). Calena and Celine were the highest yielding genotypes and had nearly the same SI. The SI relationships for seed yield were variable for genotypes among precipitation regions and showed adaptation differences (Fig. 3A, B, C, and D). Blaine Creek was stable and near average yield except for the intermediate precipitation site. GP07 was lowest yielding in all environments and had a low SI except in the intermediate precipitation environment. Calena and Celine were the two highest yielding cultivars and Calena had an SI closer to 1 than Celine except for the low precipitation environment where they were similar. These analyses should provide insight when selecting genotypes for other areas with similar precipitation.

3.2. *Oil content*

Seed oil content was determined in seven trials, including at least one trial at all locations, and ranged across genotypes from 29.6% at Pullman spring 2009 to 36.8% at Corvallis spring 2010 (Table 5). The narrowest range of oil content values among genotypes was found at Moscow spring 2008, 29.8% to 31.4%, and the widest range was at Pullman spring 2010, 30.6% to 36.1%, with both highly significant for differences among genotypes. Oil content at Pendleton and Lind fall 2010 were not different among genotypes. The overall mean oil content across seven trials was 32.1% and ranged from 30.8% to 32.9% among genotypes. Gugel and Falk (2006) found that oil content of 19 camelina accessions ranged from 38% to 43% in various environments located across western Canada.

Table 7
Pearson correlations for seed yield, grain density, oil content, plant height, and lodging for 18 camelina genotypes at two Pullman, Washington environments in 2009 and 2010.

	Grain density	Oil content	Plant height	Lodging
Seed yield	0.366***	−0.654***	0.275***	0.223**
Grain density		−0.414***	−0.232**	ns
Oil content			ns	−0.431***
Plant height				0.269***

** Significant at 0.01 probability level.
*** Significant at 0.001 probability level.

Pearson correlation coefficient between seed yield and oil content for mean values was highly significant, but only −0.216, showing a weak negative relationship across trials. Among trials, the strongest correlation was found at Pullman spring 2010 at −0.770. This relationship was likely strong because of a large range of oil values.

Mean seed oil content across the seven trials and among genotypes ranged from 30.8% for 'GP48' to 32.9% for Ligena (Table 3). Eleven of the 18 genotypes produced oil content above the 32.1% overall mean. This indicates that environment can influence seed oil content more than genotype selection. However, oil content does not appear to be always negatively correlated with high seed yield because the Pullman spring 2010 trial averaged 2965 kg/ha seed yield and was above the average of 33.7% for oil. This trial also produced the highest oil yield (seed yield × oil content) of 998 kg/ha (Table 4). Across seven trials analyzed for oil content, oil yield averaged 545 kg/ha and was strongly influenced by seed yield, the largest variant of the two components of oil yield.

3.3. Other plant characteristics

Camelina is a very small seeded crop that creates some handling difficulties. Seed weight is both an indication of seed size and a fundamental component of yield (yield = seed weight × seed number), and was determined in five trials. The grand mean for seed weight was 1.25 g/1000 seeds compared to 1.35 g/1000 seed across 30 genotypes and three environments reported by Vollmann et al. (2007). Genotypes ranged from 1.15 g/1000 seed for Columbia to 1.46 g/1000 seed GP07. Plant breeding to increase camelina seed size has been mixed as is shown in these trials, but Vollmann et al. (2007) contends that larger-seed genotypes are inferior to smaller-seed genotypes for seed yield and oil content. However, in our trials, Ligena produced above average yields, 1259 kg/ha, and the second highest seed weight, 1.406 g/1000 seed showing a genotype with larger-than-average seed can be high yielding.

Plant height, lodging, and grain density were determined in the four Lewiston and Pullman trials, although lodging only occurred at Pullman spring 2009 and 2010 (Table 6). Plant height ranged from 80.3 cm for GP07 to 97.7 cm for GP48 with a 92.4 cm average height. Lodging at the two Pullman trials averaged 16% with a high of 36% for GP48, the tallest genotype. Pearson correlations of lodging with other traits were positive for plant height and seed yield, negative for oil content, and not related to grain density (Table 7). Because lodging occurred with all genotypes at Pullman, lodging potential could increase if the plants were taller and yielded more as indicated by positive correlation. Grain density averaged 652 kg/m^3 with a narrow range from 636 to 664 kg/m^3. Camelina grain density from these trials is similar to the canola standard for grain density, 669 kg/m^3 (ASABE, 2013). Grain density was positively correlated with seed yield, but negatively correlated with oil content and plant height. In the two Pullman trials, seed yield was negatively related to oil content as previously discussed in Section 3.2 above.

4. Conclusion

Genotype adaptation in the production environment is an important component of a camelina management system. Our research quantified many of the adaptation differences that can occur for camelina across four different environments in the PNW: (i) Seed yield, yield stability, seed size, and oil content varied widely among genotypes and environments and their interaction; (ii) spring planting was superior to fall planting; (iii) the named genotypes Calena and Celine consistently produced the highest seed yield and showed the most stable adaptation across the varied environments evaluated; (iv) oil content varied more across environments than among genotypes. These results should be useful for plant breeders to assess potential variation potential and adaptation differences especially for the seed yield and oil content potential of camelina. Growers and the seed industry need to understand the variability and adaptation potential of camelina across environments to further the ongoing effort to promote camelina production.

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