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Camelina: Planting date and method effects on stand establishment and seed yield

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ABSTRACT

There has been keen interest in camelina (*Camelina sativa* L. Crantz) in recent years due to the unique fatty acid composition of the seed oil for human and animal consumption and, more importantly, the value of the seed oil to provide "green energy" to fuel commercial and military aircraft. The objective of our research was to evaluate several planting dates and two planting methods for camelina stand establishment and seed yield. Field experiments were conducted for three years at four distinct rainfed agro-environments in the Pacific Northwest, USA. Average crop-year precipitation at the sites during the three years was: Lind WA, 228 mm; Pendleton OR, 421 mm; Moscow ID (one year only), 760 mm; and Corvallis OR, 993 mm. Camelina was planted on an average of five dates at each site ($n = 55$) from early October to mid April at a rate of 6 kg/ha by either drilling seed at a shallow depth or broadcasting seed on the soil surface. Although camelina has excellent cold hardiness, the best plant stands were achieved with the late-winter and early-spring plantings. Four divergent planting date yield responses across sites were: no yield differences at Lind; increased yield with later planting dates at Pendleton; reduced yield with later plantings at Moscow (one year data); and a curvilinear response at Corvallis with the lowest yields from plantings in early fall and those after March 1 and highest yields from late-fall and mid-winter plantings. Both drilling and broadcast were effective for planting camelina with no overall advantage of either method. Seed yields ranged from <100 kg/ha during an extreme drought year at Lind to 2900 kg/ha at Moscow. Averaged across the four Pacific Northwest agro-environments in this study, we recommend: (i) late February–early March as the best overall planting date because of optimum stands and seed yield and having effective control of winter-annual broadleaf weeds with herbicide applied just prior to planting, and (ii) the broadcast method of planting as it generally equaled or slightly exceeded drilling for plant stand establishment and seed yield and can be accomplished more quickly at less expense.

1. Introduction

Camelina is a short-season annual oil-seed crop in the Brassicaceae family that has been produced for the oil in Europe for 3000 years (Zubr, 1997). European production of camelina was largely replaced by canola (*Brassica napus* L.), but limited production of camelina continues in Northern Europe. Camelina likely appeared first in North America as a contaminant in flax (*Linum usitatissimum* L.) seed (Putnam et al., 1993). Camelina is newly introduced to crop production in the USA and Canada with most production taking place in the last five years in Montana and North Dakota, a region with summer-dominant rainfall. Montana is the leading producer in recent years with a range of 3600–8100 planted hectares (NASS, 2011).

Oil content in camelina seed can range from 38 to 43% and seed protein content from 27 to 32% (Gugel and Falk, 2006). Similar to flax, high concentrations (36–39%) of linolenic acid (C18:3), an omega-3 fatty acid, in the oil makes camelina an attractive food oil crop (Gugel and Falk, 2006). While erucic acid (C22:1) concentrations in the oil are often less than 3% (Putnam et al., 1993), the 2% or lower level food standard of this fatty acid has not been widely attained, thus limiting its use as a food crop at this time (Gugel and Falk, 2006). However, camelina meal has been approved and used on a limited basis in rations for beef cattle and chickens. The oil can also be used as a feedstock for biodiesel (Fröhlich and Rice, 2005) and more recently has been under investigation as a feedstock for aviation fuel (Shonnard et al., 2010).

Dependence on imported oil and environmental concerns about excessive use of petroleum-derived fuel has led the United States

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and other countries to seek alternative and renewable energy sources such as biofuel. Jet fuel derived from camelina oil has undergone extensive testing by commercial airlines and the US military in recent years. Test results show that camelina-based hydrotreated jet fuel meets all jet engine performance expectations and significantly reduces greenhouse gas emissions compared to petroleum-based jet fuel (Shonnard et al., 2010).

Glucosinolate concentrations in the seed can vary among cultivars and range from 13 to 36 μmol/g (Schuster and Friedt, 1998). Camelina seed and raw oil have high concentrations of tocopherol, an anti-oxidant that inhibits rancidity and allows long storage without degradation (Eidhin et al., 2003).

Camelina may have potential benefits in rotation with crops in the grass family including small grain cereals and cool-season grass seeds. In the Willamette Valley of Oregon, camelina is preferred over other potential bioenergy crops because it does not have the potential to cross with *Brassica* spp. vegetable seed crops that are widely grown there (Hansen, 1998). Additionally, camelina under certain conditions can be an economically viable crop without the use of herbicide inputs (Gesch and Cermak, 2011). Camelina appears to be a competitive crop to weed species and can compensate widely as plant populations fluctuate. McVay and Khan (2011) showed no significant seed yield reduction with up to 50% stand reduction at either rosette or bolting stage. This plasticity also was evident for oil content that was only diminished when stands were reduced more than 75% at bolting.

Previous studies on the date of planting in establishment of camelina have been conducted in several environments and have provided mixed results. Urbaniak et al. (2008) reported that seed yield of camelina in the maritime provinces of eastern Canada was not influenced by the date of planting. In Nebraska, however, highest seed yields were obtained when camelina was sown in late March until mid-April (Pavlista et al., 2011). Lower seed yields were observed with early planting dates in February or early March, and with later planting dates in late April through June. Fall-planted camelina seed yields were best in Minnesota in early or mid-October rather than earlier in mid or late September (Gesch and Cermak, 2011).

The influence of planting date on camelina seed yield in the varied precipitation and soils of the Pacific Northwest states of Oregon, Washington, and Idaho, a region of winter-dominant precipitation, has not been previously investigated. Moreover, no studies have been published in the literature on methods of planting camelina. The objective of our study was to investigate how planting date and method affected stand establishment and seed yield of camelina across four diverse crop production environments.

2. Materials and methods

2.1. Overview

A 3-year field experiment was conducted during the 2008, 2009, and 2010 crop years at four sites in the Pacific Northwest to determine the most suitable planting date(s) and method of planting for rainfed camelina production. Field sites were located at Lind, WA; Pendleton, OR; Moscow, ID; and Corvallis, OR, where long-term average annual precipitation is 242, 418, 695, and 1085 mm, respectively. The climate throughout the Pacific Northwest is Mediterranean, where two-thirds of precipitation occurs from October through March and one-fourth from April through June. July through September are the driest months. Soils at all sites are more than 180 cm deep and well drained with soil textures ranging from coarse silt loam (Lind) to silty clay loam (Corvallis). The sites represent each of the four major rainfed agricultural production zones in the Pacific Northwest. All four sites were located on university-owned research farms. Precipitation (Table 1) was measured in all locations at official U.S. National Weather Service recording sites located ≤300 m from the experiments.

Table 1
Crop-year (September 1–August 31) precipitation (mm) at four sites during the 3-year study.

Month	Lind			Pendleton			Moscow	Corvallis		
	2008	2009	2010	2008	2009	2010	2009	2008	2009	2010
September	4	0	4	7	3	0	19	44	22	30
October	17	6	39	33	5	45	20	110	38	75
November	28	20	21	53	39	46	123	110	120	207
December	30	38	32	60	71	44	97	240	153	138
January	41	22	36	45	52	43	97	221	94	172
February	6	23	21	16	36	18	51	68	84	111
March	21	45	19	56	65	35	112	114	97	154
April	5	23	30	13	45	70	55	61	33	111
May	3	21	47	33	36	100	76	10	93	84
June	12	6	35	34	29	73	37	26	16	70
July	0	3	8	3	0	0	32	1	20	3
August	7	8	2	15	35	5	41	31	6	13
Total	174	215	294	368	416	479	760	1036	776	1168

Experimental design was a split plot in randomized block arrangement with planting date as the main plot and planting method as subplots. All treatments were replicated four times. The size of individual plots varied depending on the equipment and land available at each location. Individual plot sizes were 2.4 m × 30 m at Lind, 2.4 m × 10.6 m at Pendleton, 1.5 m × 6.1 m at Moscow, and 3.0 m × 15.2 m at Corvallis. Camelina was direct seeded into the standing stubble of recently harvested (no summer fallow) winter wheat (*Triticum aestivum* L.) at Lind and Pendleton. Tillage was used for seedbed preparation after wheat harvest at Moscow and Corvallis. The camelina cultivar 'Calena' was used at all locations and sowing rate was 6 kg/ha, with a typical seed weight of 1.2 g/1000 seed or about 5 million seeds/ha. Nitrogen fertilizer was applied at all sites at moderate rates based on soil test. Averaged over the three years, nitrogen application rates at Lind, Pendleton, Moscow, and Corvallis were 28, 45, 78, and 68 kg/ha, respectively. In-crop post-emergence grass weed herbicides, either Poast^{TM} (sethoxydim) or Assure II^{TM} (quizalofop-p-ethyl), were successfully used every year to control downy brome (*Bromus tectorum* L.), volunteer wheat and other grass weeds at Lind and Pendleton. No in-crop herbicides were used in Moscow or Corvallis.

2.2. Planting dates

Planting dates at all sites were intended for mid October, mid November, mid December, mid January, mid February, early March, and "last feasible" for planting. The last feasible date for planting ranged from March 15 at Lind to April 17 at Corvallis and was based on long-term experience growing spring-planted crops at these locations. We realized at the inception of the experiment that some of the planned late-fall and early-to-mid winter planting dates would not be possible due to frozen soil or snow cover (Lind, Pendleton, Moscow) or saturated soil conditions (Corvallis). As a result, planting was conducted on five dates per crop year when averaged over locations and years. At the Moscow site, only 2009 crop-year data were collected as the experiment was abandoned due to a soil herbicide carryover problem in 2008 and heavy broadleaf weed infestation in 2010. Therefore, seed yield data for 10 site years is presented in this paper.

2.3. Planting methods

Seed was planted both with a drill at a shallow (<1.0 cm) depth and by broadcasting on the surface on all planting dates. Drills and method of broadcasting varied at each location. At Lind, a Kyle hoe-opener air drill was used to plant camelina seed in 10-cm paired rows with each opener on 30-cm row spacing. This same drill was used for the broadcast treatment, but with the openers operated 12 cm above the soil surface to ensure uniform air distribution of seed. A light, five-bar tine harrow was pulled behind the drill for the broadcast treatment to gently incorporate seed into the soil. At Pendleton, drilling was done with a Fabro drill with Atom-jet shank openers on 30-cm row spacing. A "Brillon" drop seeder with dual culti-pack rollers was used for broadcast planting with the seed dropped between the dual rollers. Drilling at Moscow was accomplished with a double-disk drill on 18 cm row spacing and the broadcast treatment was established by hand spreading seed with no soil incorporation. At Corvallis, a double-disk drill with 15-cm row spacing was used for both drilling and broadcasting. For broadcasting, the tubes from the seed box to the openers were disconnected and a plywood board inserted at an angle beneath the seed cups to ensure uniform dribbling of seed onto the soil surface and then incorporated with a one-bar spike-tooth harrow.

2.4. Field measurements

Camelina stand establishment was determined from all plots every year in mid-April (Lind) and immediately after seed harvest in July (Pendleton). With direct drilling, stand establishment was measured by counting individual plants in 1-m-long row segments. A 1-m-diameter hoop (Lind) or wire frame 1-m^2 in area (Pendleton) was used to measure stands in the broadcast treatment. These measurements were obtained from three areas in each plot and the numbers then averaged.

At Lind, weed species in the experiment were identified, counted, and collected in early July every year just before seed harvest within a 3 m^2 sampling frame randomly placed in each plot. Each weed species present was counted, hand clipped at ground level, and placed in a separate paper bag. Above-ground dry biomass of each weed species was determined after placing samples in a low-humidity greenhouse for 30 days, then weighing them on a digital scale.

At all locations, grain yield was measured by harvesting the seed from plants in a swath through each plot using a plot combine with the cutting platform operated near the soil surface. All plot combines were equipped with specialized screens to properly separate the small camelina seed from the crop residue.

Water use efficiency (WUE) was calculated as kilograms of seed yield per hectare per millimeter of growing-season (September 1–August 31) precipitation. The preceding wheat crop was assumed to have extracted all available soil water by time of harvest. As camelina was planted after wheat harvest (i.e., no fallow), growing-season precipitation was the only source of water for camelina.

2.5. Statistical analysis

Analysis of variance was conducted for plant stand establishment, weed population, weed dry biomass, seed yield, and WUE (Table 2) using SAS Proc Mixed (SAS, 2002) with planting date as the main plot factor and method of planting the subplot factor. Seed yield data were transformed where necessary to improve the validity of normality and homogeneity of variance assumptions. Suspected outlying observations were included in the analysis as conclusions did not change with their inclusion or exclusion. Simple regression procedures using SAS Proc Reg (SAS, 2002) were followed to fit coefficients of determination for plant stand establishment and seed yield as affected by date of planting. All analysis of variance and regression tests were done at the 5% level of significance.

Table 2
Analysis of variance for plant population and grain yield of camelina at four sites as affected by year (Y), date of planting[a] (D), and method of planting (M).

Source	df	Plant pop.[b]	Grain yield
Lind			
Y	2	***	***
D	3	***	ns
M	1	***	***
Y × D	6	***	**
Y × M	2	***	*
D × M	3	***	***
Y × D × M	6	***	**
Pendleton			
Y	2	**	ns
D	4	***	***
M	1	*	***
Y × D	8	***	***
Y × M	2	***	***
D × M	4	ns	**
Y × D × M	8	*	ns
Moscow[c]			
D	4		**
M	1		ns
D × M	4		ns
Corvallis			
Y	1		ns
D	4		***
M	1		ns
Y × D	4		ns
Y × M	1		ns
D × M	4		ns
Y × D × M	4		**

[a] Analysis across dates only compares common planting dates among years.
[b] Plant population was measured only at Lind and Pendleton.
[c] Data were obtained during only one year at Moscow.
* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.
ns = not significant.

3. Results and discussion

3.1. Plant stand establishment

Both direct drilling and broadcasting were successful for achieving plant stands and the majority of time there were no significant differences in stand establishment between the two methods on individual planting dates at either Lind or Pendleton. When there were differences, they were evenly divided in favor of either method (Table 3). We suspect that, even though seed was placed <1.0 cm into the soil, fragile soil crusts that occur after rain showers may have sometimes hindered emergence in the direct drilled treatment. Similarly, lack of rainfall following broadcasting of seed sometimes had a severe negative effect on broadcast plant stands as can be seen in the February 15 and March 15, 2008 and March 17, 2010 planting dates at Lind (Table 3) where rainfall did not occur for more than two weeks after planting. Soil surface drying and lack of timely rain was less of a problem at Pendleton (Table 3) due to more precipitation at that location compared to Lind (Table 1).

Significant differences in stand establishment as affected by planting date occurred every year except for 2010 at Pendleton (Table 3). The fall and mid-winter plantings generally had lower plant populations than other dates (Table 3). Over-winter plant mortality was observed with dead camelina seedlings found intermixed with healthy seedlings in both planting methods. However, camelina seedlings in the two-leaf stage of development appeared

Table 3
Camelina plant populations at Lind, WA and Pendleton, OR as affected by direct drilling (DD) or broadcast (BC) method of planting from numerous planting dates during three years.

Plant population (plants/m^2)											
2007–2008				2008–2009				2009–2010			
Date	DD	BC	LSD (0.05)[a]	Date	DD	BC	LSD (0.05)	Date	DD	BC	LSD (0.05)
Lind											
October 21	59	74	ns	October 17	34	66	ns	October 21	74	113	ns
November 20	12	60	36	November 17	66	171	40	November 18	73	84	ns
February 15	74	13	44	February 17	108	281	108	January 15	145	121	ns
March 15	43	6	25	March 1	87	220	68	February 11	202	85	ns
LSD (0.05)[b]	23	14		March 15	159	183	ns	March 2	178	38	108
				LSD (0.05)	64	86		March 17	137	3	70
								LSD (0.05)	70	95	
Pendleton											
October 23	22	15	ns	November 17	14	30	ns	November 2	9	14	ns
December 21	4	14	ns	January 12	40	69	9	January 22	28	42	ns
February 12	36	41	ns	February 19	31	51	ns	February 10	31	38	ns
March 5	94	41	17	March 17	50	82	6	March 2	46	48	ns
March 22	38	23	7	March 27	68	73	ns	March 11	20	39	ns
April 1	54	37	ns	April 6	99	71	ns	March 24	44	54	ns
LSD (0.05)	29	26		LSD (0.05)	31	34		LSD (0.05)	ns	ns	

[a] Within row values show LSD (0.05) for DD versus BC method of planting for each planting date.
[b] Within column values show LSD (0.05) for both planting methods over all planting dates.

to have excellent tolerance to extreme cold as they withstood −23 °C air temperature for 8 h with no snow cover and sustained winds of 32 km/h at Lind in December 2008 with approximately 70% survival rate. Such cold tolerance is similar to that of winter wheat, the dominant crop in the region.

Overall, stand establishment at Lind was greater than at Pendleton even though seeding rate was the same at both locations and Lind has the harsher growing environment (Table 3, Fig. 1). We attribute these differences to the time at which stand data were collected. At Lind, stand counts were measured in mid April compared to after seed harvest in July at Pendleton, i.e., some plants died during the spring and early summer.

Analysis of variance showed that plant stands at both Lind and Pendleton were significantly affected by year, date of planting, and method of planting and significant interactions of these factors also occurred (Table 2). The only interaction that was not significant was date × method at Pendleton. The interactions reflect the aforementioned wide variability of data within and across years.

Coefficients of determination and fitted regression lines to describe the relationship of planting date and plant stand establishment are shown in Fig. 1. The trend was for better stands with the later planting dates at both locations. Although this relationship was not statistically significant at Lind due to wide data scatter over the three years, a significant relationship ($r^2 = 0.42$, $P < 0.001$) occurred at Pendleton.

3.2. Weeds

Winter annual broadleaf weed species that were a factor in the Lind experiment were tumble mustard (*Sisymbrium altissimum* L.) and tansy mustard (*Descurainia pinnata* Walt.). Application of herbicides to control these weeds prior to the late-winter planting dates was not possible as the fall and early-winter planting treatments were intermixed throughout the experiment area. Both of these mustard species are easily controlled when glyphosate [N-(phosphonomethyl)glycine] is applied prior to planting camelina in mid-to-late winter or early spring. Lack of opportunity to control fall-germinating broadleaf weeds is a disadvantage of planting camelina in the fall or early winter.

Russian thistle (*Salsola iberica* L.) (Young, 1986) was, by far, the major spring annual broadleaf weed of importance at Lind. Russian thistle becomes established in April or later after the period of severe frosts. The late-winter camelina planting averaged 24 Russian thistle plants/m^2 compared to six plants/m^2 for the fall plantings. Dry biomass of Russian thistle measured at camelina seed harvest in July averaged 15 and 267 kg/ha for the fall and late-winter camelina planting dates, respectively; in this case showing an advantage of fall planting for weed control.

The application of grass weed herbicide to established camelina plants was effective in controlling downy brome at Lind and Pendleton. Therefore, the incorporation of a broadleaf crop such as camelina in cereal-based cropping systems offers an excellent opportunity to control this major winter annual grass weed (Young et al., 1996). In late winter and spring plantings, downy brome was controlled with the pre-plant application of glyphosate.

3.3. Seed yield

3.3.1. Planting method

From a total of 55 planting dates at four locations over three years, planting method significantly affected camelina seed yield on 13 dates (24% of the plantings, Table 4). Of these 13, broadcasting produced higher seed yield than drilling on 10 dates. The advantage of broadcast planting was most apparent at Pendleton where this method significantly increased seed yield over drilling on 44% of the planting dates. There were no yield differences between the two methods at Pendleton on the other planting dates (Table 4). Greater seed yield with broadcasting over drilling at Pendleton occurred mostly in the fall and mid-winter planting dates and never in spring planting dates (Table 4). We do not have an explanation for this other than to speculate that winter-annual weed pressure (not measured at Pendleton) may have been greater in the direct-drill treatment due to 30-cm-wide row spacing whereas broadcast seed was more uniformly distributed to provide better competition against weeds. On the four planting dates (three at Lind and one at Moscow) where seed yield was significantly less with broadcasting versus drilling, we suspect that a dry surface soil combined with lack of precipitation for several weeks after planting was the likely reason. Seed yield differences between planting methods at Lind were always associated with differences in plant stand, but this was not always the case at Pendleton (Tables 3 and 4). Planting method had no effect on seed yield at Corvallis except for one planting date.

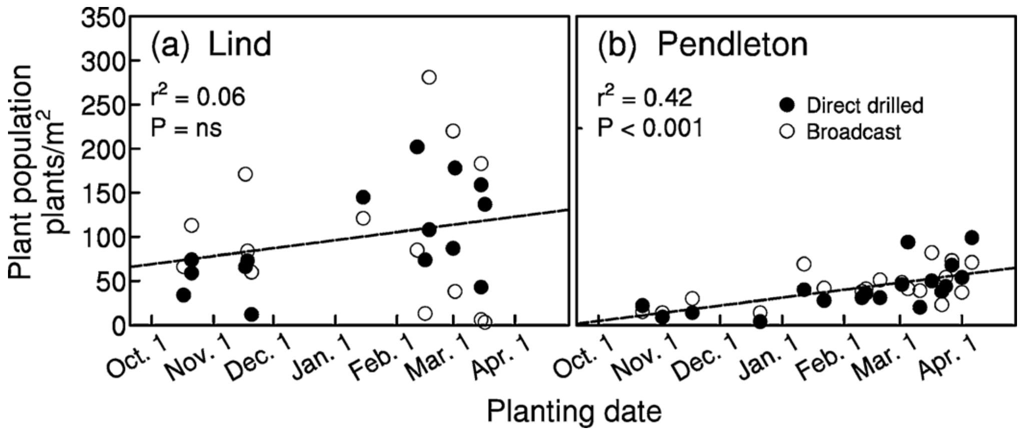

Fig. 1. Coefficients of determination for regression models to describe the relationship of camelina plant populations using both direct drilled and broadcast methods on numerous planting dates over three years at Lind, WA and Pendleton, OR.

Averaged over the three years, planting method had a highly significant ($P<0.001$) effect on seed yield at Lind and Pendleton combined with significant year × method and date × method interactions (Table 2). The date × method interaction at Lind is explained by neither planting method having an overall advantage over the other and, at Pendleton, because the broadcast method had higher seed yield from the fall and winter planting dates but not from the spring plantings (Table 4). Method of planting had no significant main effect on seed yield or date × method interaction at Moscow or Corvallis (Table 2).

3.3.2. Planting date

Camelina seed yield trends as affected by planting date differed by location. If one excludes the 2008 data from Lind (near complete crop failure data due to extreme drought), there was a clear tendency for higher seed yields with late-winter and early-spring plantings compared to fall and mid-winter planting dates at both

Table 4
Camelina seed yields using direct drill (DD) and broadcast (BC) methods on numerous planting dates at four locations over three years.

Yield (kg/ha)											
2007–2008				2008–2009				2009–2010			
Date	DD	BC	LSD (0.05)[a]	Date	DD	BC	LSD (0.05)	Date	DD	BC	LSD (0.05)
Lind											
October 21	114	150	ns	October 17	483	375	ns	October 21	935	832	ns
November 20	28	100	69	November 17	516	631	41	November 18	791	801	ns
February 15	132	41	43	February 17	558	564	ns	January 15	907	688	ns
March 15	58	4	ns	March 1	569	597	ns	February 11	941	794	ns
LSD (0.05)[b]	ns	53		March 15	584	582	ns	March 2	1336	955	ns
				LSD (0.05)	102	ns		March 17	996	519	403
								LSD (0.05)	428	ns	
Pendleton											
October 23	838	1093	211	November 17	446	909	282	November 2	143	436	134
December 21	351	660	ns	January 12	928	1600	193	January 22	557	1148	519
February 12	1348	1324	ns	February 19	711	1048	ns	February 10	896	1559	305
March 5	1715	1598	ns	March 17	1597	1772	114	March 2	1576	1606	ns
March 22	1488	1298	ns	March 27	1404	1700	ns	March 11	1058	1304	ns
April 1	1454	1428	ns	April 6	1374	1449	ns	March 24	1551	1584	ns
LSD (0.05)	609	521		LSD (0.05)	579	469		LSD (0.05)	743	931	
Moscow[c]											
				October 31	2899	2550	ns				
				December 6	2536	2443	ns				
				February 17	2812	2325	332				
				March 27	1695	1640	ns				
				April 15	1712	1700	ns				
				LSD (0.05)	1080	847					
Corvallis											
November 9	1673	2281	ns	September 30	454	435	ns	November 3	1565	1813	ns
December 13	995	557	ns	October 29	1641	1312	ns	November 23	1509	1431	ns
January 23	2092	1961	ns	December 1	1669	1847	ns	February 19	1889	1942	ns
February 18	1515	1756	ns	January 24	1588	1874	165	March 19	1426	1388	ns
April 13	685	735	ns	February 5	1877	1788	ns	LSD (0.05)	456	234	
April 17	297	262	ns	February 20	1422	1495	ns				
LSD (0.05)	488	1161		April 6	605	554	ns				
				LSD (0.05)	712	697					

[a] Within row values show LSD (0.05) for DD versus BC method of planting for each planting date.
[b] Within column values show LSD (0.05) for both planting methods over all planting dates.
[c] Data were obtained during only one year at Moscow.

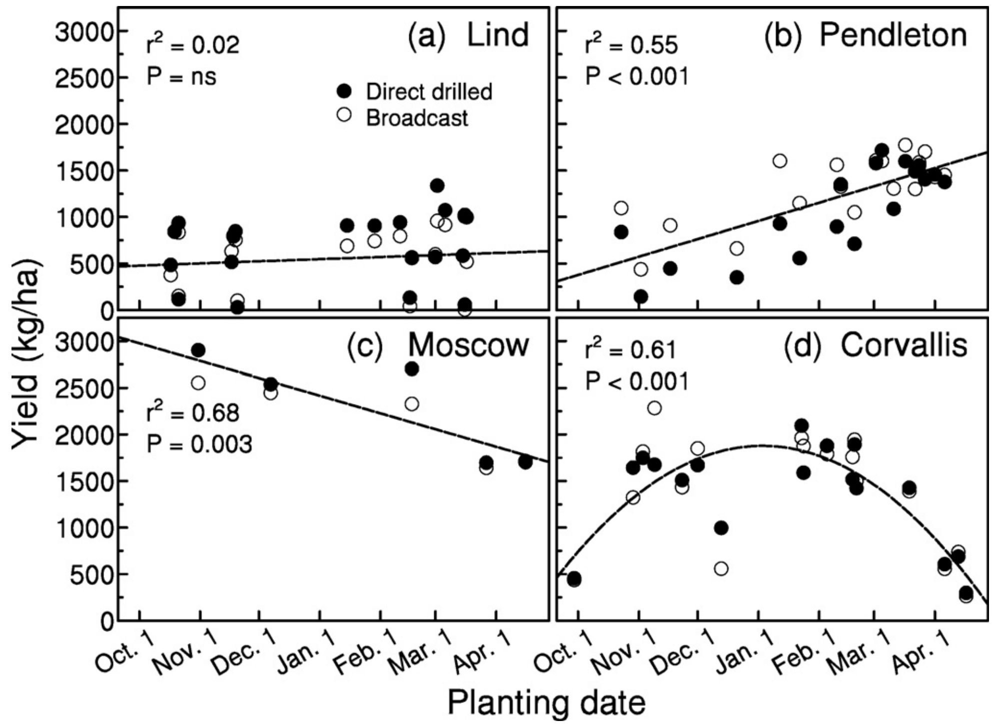

Fig. 2. Coefficients of determination for regression models to describe the relationship of camelina seed yield and planting date using both direct drilled and broadcast methods of planting at four locations over three years in the Pacific Northwest.

Lind and Pendleton (Table 4). However, the opposite was true at Moscow, although we have only one year of data from that site. At Corvallis, the late-fall and mid-winter planting dates produced the greatest seed yield during all years (Table 4). Corvallis has the greatest annual precipitation (Table 1), but a significant portion of this precipitation can be lost through drainage. The silty clay loam soil at Corvallis is well drained and dries quickly once winter rains diminish. Small, shallowly rooted plants from spring plantings can easily become drought stressed.

Downy mildew caused by *Hyaloperonospora camelinae* (Putnam et al., 2009) was evident in 2009 and 2010 at Corvallis and may have contributed to seed yield decline in those years. Extremely heavy rainfall and associated humidity at Corvallis in May 2009 (Table 1) likely contributed to the incidence of downy mildew. In plants where downy mildew was most severe, abortion of lower pods (manifested as red pods) in the inflorescence was observed. The white hyphae and sporangiophores were concentrated early in the youngest portions of the inflorescence and at maturity red aborted pods were evident, contributing to lower seed yields. Unusually wet conditions between March and the end of June (164% of normal) in 2010 may have contributed to low seed yields in 2010 since downy mildew was again evident.

Regression lines were fitted to show the relationship of planting date on camelina seed yield averaged over three years and both planting methods. There was no effect of planting date on yield at Lind (Fig. 2a). Urbaniak et al. (2008) also found that there was no effect of planting date on seed yield of camelina in eastern Canada. At Pendleton (Fig. 2b), seed yield improved significantly and proportionately moving from fall to spring planting dates. Conversely, at Moscow, the highest seed yields were achieved with fall planting and yields decreased significantly when planting was delayed until the spring (Fig. 3c). Yet another unique yield response, a curvilinear pattern, was measured at Corvallis (Fig. 3d) where the lowest yields occurred with early fall and spring planting dates and there was a broad planting window from early November and through the winter where yields were relatively uniform. The seed yield response pattern at Corvallis was similar to the one reported by Pavlista et al. (2011) in Nebraska where early and late planting dates produced the poorest seed yields. Best seed yields at Corvallis were found when planted in late fall and mid-winter whereas in Nebraska, best seed yields were attained in late winter and early spring.

Analysis of variance statistics for camelina seed yield as affected by planting date averaged over three years showed no differences at Lind, but highly significant differences at Pendleton, Moscow, and Corvallis (Table 2). There were significant year × date and date × method interactions at Lind that are explained by the extreme drought, less than average precipitation, and above-average precipitation during the 2008, 2009, and 2010 crop years, respectively (Table 1) and the fact that neither planting method showed a consistent advantage over the other. Pendleton had highly significant year × date and date × method interactions (Table 2) because most, but not all, fall and early-winter planting dates reduced seed yield and since the broadcast method was superior to direct drilling in many of the fall and winter plantings but

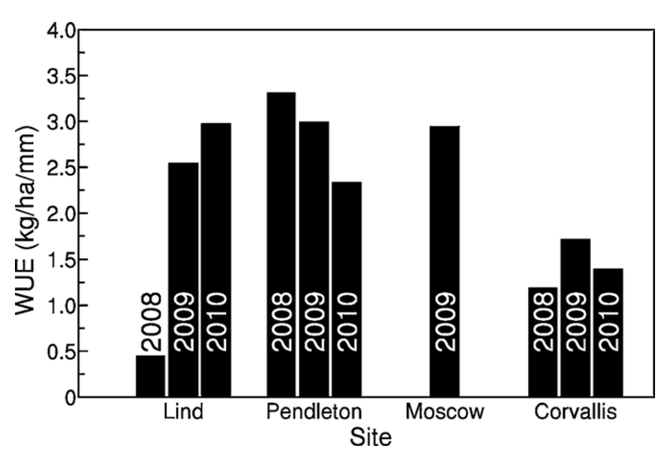

Fig. 3. Water use efficiency (WUE) of camelina grown at four sites over three years. Data for each site are the average from all planting dates and both planting methods during the year.

never from the spring plantings (Table 4). There were no two-way interactions at Moscow or Corvallis (Table 2).

3.4. Water use efficiency

Water use efficiency was extremely low at Lind in 2008 because of near complete crop failure due to extreme drought. Excluding the 2008 Lind data, WUE at Lind, Pendleton, and Moscow was relatively uniform, averaging 2.8 kg seed/ha/mm (Fig. 3). The uniformity in WUE across these three diverse locations, where average annual precipitation ranges from 242 to 695 mm, indicates that camelina seed yield potential can likely be accurately predicted based on crop-year precipitation. This will be an important factor for farmers in making their decision whether or not to grow camelina.

Water use efficiency at Corvallis averaged only 1.5 kg seed/ha/mm and was consistently low for all three years of the experiment (Fig. 3). Saturated soils, downy mildew, and water drainage through saturated soils, as previously mentioned, were likely factors contributing to the low WUE. Corvallis receives 1085 mm average annual precipitation and is a suitable environment for profitable production of many crops species. Based on yield averages, our data suggest that camelina may likely fit best in the drier Inland Pacific Northwest (i.e., Lind, Pendleton, Moscow) rather than in the wetter Corvallis location.

4. Summary and recommendations

Our data from 55 planting dates using two planting methods over 10 site years in the Pacific Northwest indicate:

1. Camelina can be successfully sown over a wide range of planting dates from early fall to early spring. Fall-planted camelina has excellent cold tolerance, similar to that of winter wheat. However, due primarily to lack of in-crop herbicides to control winter-annual broadleaf weeds, we recommend that farmers apply glyphosate or other non-soil residual burn-down herbicide in mid-to-late February to control weeds, followed by late February–early March camelina planting.
2. Both drilling and broadcasting were effective methods for planting camelina. There was no overall advantage of one method over the other at Lind. There were three occasions at Lind, however, where broadcast stands and subsequent seed yield were significantly reduced compared to drilling when no precipitation occurred for several weeks after planting. At Pendleton, seed yield from broadcast planting was superior to drilling for fall and early-to-mid winter planting dates, presumably due to better winter annual broadleaf weed control as the drill used at Pendleton had relatively wide (30 cm) row spacing. There were no consistent differences in seed yield as affected by planting method at Moscow and Corvallis. From an economic standpoint, we recommend farmers use broadcast planting combined with some form of light incorporation of seed into the soil. Broadcast air-driven applicators ≥ 20 m wide are common rental inventory of local chemical dealers. These applicators easily allow planting of 150 ha/day. Conversely, grain drills are not as wide, more expensive to rent or own, generally need to be operated at a slower speed, and thus more time is required to plant equivalent land area.

Finally, although not part of this experiment, farmers need to be mindful that camelina produces relatively little residue. With heavy tillage, soil erosion may be a problem during or after camelina production. To reduce the potential for soil erosion, we recommend that (i) camelina be planted directly into the standing and undisturbed stubble of the previous crop (i.e., no tillage) and (ii) minimal or no tillage be conducted after camelina seed harvest and before planting the subsequent crop. This is especially important if a year-long fallow period is scheduled in the rotation after camelina seed harvest.

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