Camelina: Seed Yield Response to Applied Nitrogen and Sulfur

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Abstract

Camelina (*Camelina sativa* L. Crantz) has received worldwide attention in recent years as a biofuel crop and as a broadleaf option in cereal-based cropping systems. The objective of our 3-year study was to determine camelina seed yield and nitrogen use efficiency (NUE) as affected by six applied nitrogen (N) rates at four rainfed sites in the Pacific Northwest (PNW) of the United States. An N + sulfur (S) variable was also included. Seed oil content as affected by applied N and S was also evaluated in 2010. The four sites and their average annual crop-year precipitation during the three years were Lind, WA (228 mm); Pendleton, OR (421 mm); Moscow/Pullman, ID (695 mm); and Corvallis, OR (1085). The majority of precipitation occurs in the winter and summers are comparatively dry. Camelina responded differently to applied N among sites based upon precipitation and available soil N. Seed yield did not respond to N rate treatments at Lind, presumably due to sufficient soil residual N and limited precipitation. Seed yield increased with applied N at Pendleton, Moscow/Pullman, and Corvallis. Optimum applied N rates ranged from 0 to 90 kg ha-1 depending on annual precipitation and soil available N. Maximum seed yield increases attributable to applied N ranged from 19% at Pendleton to 93% at Moscow/Pullman. Camelina NUE was greatest at Moscow/Pullman although it decreased gradually with increasing applied N rates at all sites. Lind, Pendleton, and Corvallis had the same NUE of -0.06 kg seed for every kg of available N. Camelina did not respond to applied S at any site. Seed oil content was not affected by applied N or S. Based upon the results of this study, camelina requires about 12 kg N ha^{-1} per 100 kg of expected seed yield.

Keywords: Camelina, Biofuel crops, Sustainable energy, Nitrogen use efficiency, Dryland cropping systems, Pacific Northwest USA.

1. Introduction

There has been much recent interest in the oilseed camelina as a low greenhouse-gas-emission biofuel crop, and especially as a feedstock for jet aviation fuel (Shonnard et al., 2010). Camelina is an annual plant with small seed (700,000 seed kg^{-1}) that has been cultivated in Europe for centuries. Camelina has a short growing season, requiring only 85 to 100 days from emergence to maturity when planted in the spring. Plants grow from seedlings to rosettes to mature plants reaching 0.5 to 1.0 m in height. Leaves are 50 to 75 mm in length, arrow-shaped and pointed with smooth edges. Stems are branched and bear seedpods 5-6 mm in diameter. The growth stages of camelina have been described in detail by Martinelli and Galasso (2011). Seed contains 32 to 43% oil that is an excellent feedstock for biodiesel, aviation fuel, or other liquid fuel (Moser, 2010). Camelina is a good potential fit for rainfed crop rotations of the PNW because it is more drought tolerant, less susceptible to freezing in the seedling stage, and has fewer insect pests compared to rapeseed (*Brassica napus*) or pulse crops (Henderson et al., 2004). Camelina has potential as a broadleaf crop option over the large cereal-based cropping region of the inland PNW. A desirable feature of camelina is the ability to be sown on frozen soil (frost seeding) with limited or no tillage (Robinson, 1987; Putnam et al., 1993).

Camelina has several unique agronomic features, including adaptability to marginal soils, short growth cycle and, if compared to rapeseed, a greater resistance of siliques to dehiscence. Gesch and Cermak (2011) found camelina to be a viable winter-sown crop in the northern corn belt of the USA. Camelina is productive under a wide range of plant stands (McVay and Khan, 2011). In addition, camelina is resistant to diseases such leaf spot (*Alteraria brassicae*) (Browne et al., 1991; Sharma et al., 2002) and insect pests (Henderson et al., 2004).

Together these characteristics highlight the agronomic potential of this species and serve in promoting camelina as a suitable candidate for sustainable cropping systems.

Camelina was grown on a limited basis in the northern Great Plains of the USA in recent years with 8,100 hectares planted in 2010 (NASS, 2012). Camelina production has been limited but increasing in the PNW. Research-based information is lacking to provide basic agronomic recommendations for this crop. Schillinger et al. (2012) demonstrated that seed yield response of camelina to planting date varied across four diverse sites in the PNW. Recommended N and S application rates for camelina production in the PNW are unknown because of the lack of previous studies and the varied crop production environments in the region, although a few such studies have been conducted elsewhere in the USA (Putnam et al., 1993; McVay and Lamb, 2008; Jackson, 2008). Based on limited research in Montana, McVay and Lamb (2008) suggested that N management for camelina should follow recommendations for canola (*Brassica napus* L.). Recommendations for canola in the PNW are predicated on the expected yield of the crop, N requirement, soil available N, and cropping history (Wysocki et al., 2007a). Following N, sulfur is the most limiting element in the PNW and oilseed crops are known to have greater S requirements than cereals.

Rainfed cropping in the PNW can be divided into four distinct rainfed agricultural production zones that vary widely in precipitation, elevation, soil conditions and temperature (Douglas et al., 1990; Schillinger et al., 2006). In the PNW, camelina will most likely be grown following a cereal crop. It is anticipated that camelina can be grown to both diversify and intensify (less summer fallow) rainfed cereal-based cropping systems. To grow camelina successfully in the region will require crop performance information from a wide range of environments. The objective of our study was to assess the impact of N and S fertility on camelina seed yields across four diverse rainfed cropping zones of the PNW. Individually each site in this study is representative of from 0.2 to 1.5 million cultivated hectares. Information from this study on N and S fertility management for camelina has broad application in the PNW and other Mediterranean climates around the world.

2. Materials and Methods

2.1 Locations

Nitrogen and S fertility studies were conducted during the 2008, 2009, and 2010 crop years at four sites. Lind, Pendleton, and Moscow/Pullman are located in the inland region east of the Cascade Mountains and Corvallis is located in the Willamette Valley of western Oregon (Fig. 1). Environmental conditions vary widely among the four locations. Soil type, average annual precipitation, elevation and growing degree-days (GDD) for all sites are shown in Table 1. Moscow/Pullman and Pullman represent the same cropping environment. In 2008 and 2009, the experiment was conducted near Moscow and in 2010 near Pullman, 14 km apart (Fig. 1), and have the same soil type.

Growing degree days (Table 1) are reported from January 1 to August 1 because camelina is a spring crop that will have matured by the end of July. Average long-term annual precipitation among sites ranges from 242 to 1085 mm, elevation ranges from 70 to 809 m, and GDD from 1109 to 1524. Of the three locations east of the Cascade Mountains, Moscow/Pullman is the coolest (fewest GDD) and receives the most precipitation. Precipitation is sufficient for continuous annual cropping (no fallow) and a common crop rotation is winter wheat (*Triticum aestivum* L.)-spring cereal-spring pulse. Lind is by far the driest of the four sites and has about the same cumulative GDD as Corvallis, though the seasonal distribution is different. Winter wheat-summer fallow is the customary crop rotation at Lind and is in a wide geographic area that receives less than 350 mm annual precipitation. Pendleton has the greatest GDD and receives 80% more annual precipitation than Lind. Crop rotation options at Pendleton are varied and include winter wheat-summer fallow, winter wheat-spring crop-summer fallow, and winter wheat-spring pea (*Pisum sativum* L.). Corvallis is at a low elevation in the Willamette Valley, receives high precipitation, and has a more moderate climate than sites east of the Cascades. Numerous annual and perennial crops are successfully and profitably produced at Corvallis. Grass seed is the major crop in the Willamette Valley with wheat as secondary crop in rainfed production. Vegetable and other high-value crops are also important where irrigation is available.

2.2 Overview of Experiment

Annual precipitation at the four locations ranged from 174 to 1168 mm during the study period (Table 2). Nitrogen and S rates were evaluated based upon expected yield at each respective study site. Based on earlier work, yields were expected to range from 500 to 2200 Kg ha^{-1} depending on annual precipitation (Guy and Lauver, 2007; Wysocki and Sirovatka, 2008). Treatments consisted of six incremental N rates with and without applied S (Table 3). Because of lower yield potential, S was applied at two N rates at Lind and at one N rate at Pendleton. Fertilizer rates were identical for Moscow/Pullman and Corvallis with 0 or 22 kg S ha^{-1} applied factorially to all N rates (Table 3). Experimental design at all locations was a randomized complete block design with four replications.

Soils at each location were sampled for available N (NO_3^- and NH_4^+) and S prior to planting. Soil NO $_3$-, NH_4^+, and S were measured using chromotropic acid, 2N KCL extraction and turbidimetric methods respectively (Gavlak, et al. 2003). At Lind and Pendleton, soil samples were collected and analyzed in 0.3 m increments to a depth of 1.2 m and at Moscow/Pullman and Corvallis in 0.3 m increments to a depth of 0.6 m. It is customary to sample to greater depth in the dry regions because deep $N0_3^-$ is used to estimate available N whereas in the wetter areas deep samples are not as useful in predicting available N due to high leaching potential and greater release of mineralized N. At Lind, liquid urea-ammonium nitrate solution (32-0-0) (tank mixed with ammonium thiosulfate for the N + S treatments) was applied to plots as a broadcast spray in mid-February. Nitrogen was applied immediately before planting at Pendleton and Corvallis as dry, granular urea (46-0-0) with ammonium sulfate (21-0-0-24) as the S source. Fertilizer was applied with a disc applicator on 20 cm spacing at a depth of 7.5 cm at Pendleton whereas it was broadcast then incorporated with tillage at Corvallis. At Moscow/Pullman, N was broadcast as granular urea and S was applied as a broadcast spray of ammonium thiosulfate (10-0-0-26). Both were applied soon after planting.

Planting rate was 6 kg seed ha^{-1} with the cultivar ‘Calena’ at all sites. Planting dates varied by location and year, but occurred February through April (Table 2). These dates are typical for planting of spring crops for the locations. Recently reported research (Schillinger et al., 2012), shows these dates achieved the highest camelina seed yield potential. Dates in this study are also consistent to those suggested for planting camelina in Nebraska (Pavlista et al., 2011). Glyphosate [N-(phosphonomethyl)glycine] was applied for weed control prior to planting. In-crop post-emergence grass weed herbicides, either Poast™ (sethoxydim) or Assure II™ (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 at Moscow/Pullman or Corvallis. Trials at all locations were planted following an immediate previous crop (no summer fallow, Table 2). Trials at Lind were direct seeded into standing wheat stubble with a hoe-opener drill and at the other locations tilled seedbeds were prepared using customary tillage practices for each location and planted with a double disc drill. Drill row spacing was 15 cm at all locations. Plot dimensions respectively at Lind, Pendleton, Moscow/Pullman and Corvallis were 2.5 x 30, 1.5 x 12, 1.5 x 6.1, and 3 x 15 m.

2.3 Measurements

Camelina seed was harvested using plot combines. The lower sieve of the combines had 3 mm round or square holes for desired cleaning. Harvested areas respectively for Lind, Pendleton, Moscow/Pullman and Corvallis were 46.5, 16.7, 9.2 and 23 m^2. Yield was calculated from the weight of harvested seed at 8% moisture. Trials were harvested at maturity during July or August depending on location. Nitrogen use efficiency was calculated by dividing seed yield by total N (pre-plant available N + applied N) (Rathke et al., 2006) for each year at each location. Oil content from seed harvested from all treatments at all locations in 2010 was measured by nuclear magnetic resonance (Krygsman et al., 2004).

2.4 Statistical analyses

Data were analyzed with the Statistix 9 program (Analytical Software, 2010). The AOV/AOCV (general AOV/AOCV, randomized complete block) was used to partition error terms and degrees of freedom among sources of variation from each location over years (Table 4). Data from each site were analyzed individually because of the major differences in precipitation and temperature and consequent yield. The effect of S was analyzed by comparing the N rate(s) with and without S. Linear regression procedures were used to determine coefficients of determination and to fit seed yield response lines for applied N and NUE.

3. Results

3.1 Lind

The 2008 experiment failed due to extreme drought (Table 2) when only 174 and 47 mm of crop-year and growing season precipitation occurred, respectively. Trials were successful in 2009 and 2010. Data on response to applied N are presented in Table 3 and Fig. 2. There was a difference in yield response between years, but no significant within-year or between-year response to applied N, S, or N x S interactions (Tables 3 and 4). Since there was no significant response to applied S nor a N x S interaction (Table 4), seed yield data in Table 3 are presented as a 2-year average at Lind rather than for individual years. Though pre-plant available soil N was greater in 2009 than in 2010 (Table 2), camelina responded nearly the same to all rates of N in both years (Fig. 2). Although the r^2 and P value at Lind are high and statistically significant, respectively (Fig. 2), this shows that the coefficient of determination has statistically significant predictive capability. In other words, the r^2 and corresponding P value show that the relationship between the dependent variable Y and the predictor variable X is not explained by chance. Therefore, although the slope for Lind in Fig. 2 is relatively flat, the high r^2 and low P value is correctly interpreted that the relationship between applied N and seed yield is strong (i.e., one can be predicted from the other). The slope of the NUE regression line was -0.06 kg seed yield for each kg of applied N (Fig. 3).

3.2 Pendleton

Data on response to applied N and S for three years at Pendleton are presented in Table 3 and Fig. 2. There was a difference in yield response among years ($P < 0.05$) and a response to N rates ($P < 0.01$) (Table 4). There was no response to applied S in any year (Table 4). Interactions for S x N could not be tested because S was only applied at the 50 kg ha^{-1} N rate. Seed yields responded nearly linearly with increased N rate; however, the first increment of applied N generally provided the greatest increase in yield. The regression line for NUE at Pendleton with increasing N applications has an identical slope (i.e., $y = -0.06$) as that for Lind (Fig. 3). Applied N rates had no effect on seed oil content (Table 3). Thus, oil yield is directly proportional to seed yield.

3.3 Moscow/Pullman

At Moscow/Pullman, 3-year average seed yields ranged from 1129 to 2198 kg ha^{-1} and increased incrementally with applied N rates up to 90 kg ha^{-1} (Table 3). There was no yield response to S at any of the six N+S versus N alone comparisons (Table 3). Camelina yield increased in a near linear response with increasing N rate in 2009 and 2010, but the yield response line was relatively flat in 2008 (Fig. 2), presumably because (i) pre-plant available N was high, (ii) crop-year precipitation relatively low, and (iii) late planting date in 2008 compared to the other years reduced yield potential(Table 2). This resulted in a highly significant ($P < 0.001$) N x year interaction, the only significant interaction at any location in the entire study (Table 4). A similar lack of response at Moscow/Pullman to applied N in 2008 is seen in the NUE data (Fig. 3). Seed oil content was unaffected by applied N or S (Table 3).

3.4 Corvallis

Camelina seed yield at Corvallis over the three years ranged from 1219 to 2009 kg ha^{-1}. Although there was a highly significant effect of applied N on seed yield, these differences were found between the highest and lowest N rates but not among the middle rates (Table 3). Similar to Moscow/Pullman, there was no yield benefit of added S at any of the six N+S rates compared to N alone (Table 3). There were no N x year interactions (Table 4). Seed yields were considerably greater across all N rates in 2008 compared to the other years. Seed yields across N rates were almost identical in 2009 and 2010 despite crop-year precipitation of 776 versus 1168 mm, respectively. As reported by Schillinger et al. (2012) from a camelina planting date and method experiment conducted at Corvallis during 2008 to 2010, downy mildew caused by *Hyaloperonospora camelinae* (Putnam et al., 2009) was evident in 2009 and 2010 and likely contributed to seed yield decline. As with the other locations, NUE at Corvallis was highly correlated with applied N. The slope of the regression line (y = -0.06x) was identical to that at Lind and Pendleton (Fig. 3). Seed oil content was unaffected by applied N or S (Table 3).

4. Discussion

Camelina seed yield ranged widely across the four locations due to differences in annual precipitation and soil available N. However yields were within the range expected from previous work (Guy and Lauver, 2007; Wysocki and Sirovatka, 2008). There was no response to applied S at any site during any year. We speculate that a soil test concentration above 10 mg kg^{-1} in the top 0.3 m of soil is adequate at all locations for S, but recommend modest additions of S when soil tests are below this level. This recommendation agrees with fertilizer guides for canola (Wysocki et al., 2007a) and wheat (Wysocki et al., 2007b) in the PNW.

There was a complete crop failure at Lind in 2008 when crop-year precipitation was only 174 mm, and no response to applied N in the other years due to relatively low yield potential at this dry location with relatively high soil available N (Table 2). While the ANOVA (Table 4) shows, there was not a significant response to applied N at Lind, the regression shows there was a trend to increase yield with greater N rates, but very little grain was produced with additional applied N. From a practical standpoint, it is not economical to apply N to get small increases in grain yields in this environment.

The customary farming practice in a wide geographic area surrounding Lind is winter wheat-summer fallow. However, camelina was planted in lieu of fallow. Camelina is considered a drought-tolerant, modest input crop and the only realistic rotation for this crop is winter wheat-camelina-summer fallow. Results from Lind suggest that 60 kg ha^{-1} or less available N is all that is required for camelina to reach its yield potential at this location. In years of average or above-average precipitation in low rainfall areas of the PNW such as Lind, camelina could likely be grown in lieu of fallow without additions of N fertilizer. Camelina captures unused N applied in the previous wheat crop. Production of yellow mustard (*Sinapis alba* L.), and safflower (*Carthamus tinctorius* L.) following winter wheat in this environment has been shown to be risky and not economical (Schillinger et al., 2007), but camelina appears to be more promising than these crops.

Camelina at Pendleton responded similarly to applied N in all three years (Fig. 2). Yields continued to rise with incremental N application, but the economic threshold for N application was probably reached at the first or second increment of applied N (observation, specific economic analysis was not done). When yield responses are correlated with applied N over the three years, there was significant linear response (Fig. 2). In the intermediate precipitation zone of the PNW (300-to 450-mm annual) such as Pendleton, soil residual N is generally insufficient to supply adequate N for optimum crop yield. An applied N response was obtained even with ≈ 100 kg ha^{-1} pre-plant available soil N, indicating that the most economically viable yields were probably attained with about 30 kg ha^{-1} applied N. This suggests that total available N (soil N + applied N) of 120 to 130 kg ha^{-1} is required to optimize yield at Pendleton. This value is lower than that recommended for spring wheat (Lutcher et al., 2007) or canola (Wysocki et al., 2007a). The regression showed that camelina seed yield increased by 4.9 kg ha^{-1} for each kg of applied N ha^{-1}. Yields and NUE for camelina suggest it is a viable spring oilseed in areas of PNW receiving 350-400 mm of annual precipitation, if markets for camelina are available and prices are comparable to other spring oil seeds.

At Moscow/Pullman, camelina responded well to applied N in 2009 and 2010, whereas only a slight N response was found in 2008. The low response in 2008 is attributed to late planting and high available soil N. Combined over years, the regression showed that yield increased by 9.9 kg ha^{-1} for each kg of applied N ha^{-1}. Like Pendleton, yield at Moscow/Pullman and Corvallis, continued to increase numerically, if not always significantly, in response to applied N in all years. Yields generally continued to rise with incremental N application even at the highest level. Even though Corvallis receives more than twice the annual precipitation of Pendleton, 3-year average seed yields between these sites were similar. Moscow/Pullman had substantially greater 3-year average seed yield than Corvallis despite having only 74% of Corvallis's average precipitation (Table 3). This indicates, as has also been reported by Schillinger et al. (2012), that inland PNW locations are better suited for camelina production than the Willamette Valley of western Oregon. Our data suggest that the optimum N application rate for Moscow/Pullman and Corvallis may be 60 to 90 kg ha^{-1}, or 140 to 170 kg ha^{-1} total available N.

Applied N increased the seed yield of camelina at all sites except Lind, but the yield increases were maximized between 44 and 88 kg N ha^{-1} depending on location (Table 3). Similar results were reported under high precipitation conditions in eastern Canada; camelina seed yield increased with N rates up to 60 kg N ha^{-1} or 80 kg N ha^{-1}, depending on location (Urbaniak et al., 2008).

Nitrogen use efficiency for camelina declined at all locations with increasing N rates (Fig. 3). The rate of decline (0.06 kg seed NUE decline for every added kg of N) was identical for Lind, Pendleton, and Corvallis (Fig. 3). Nitrogen use efficiency for camelina has not been previously reported in the literature; however, NUE values for canola range from 12 to 26 kg seed kg N^{-1} (Hocking et al., 1997; Svečnjak and Rengel, 2006). N recommendation per unit of grain produced to achieve optimum yield, would be lower for camelina than other spring oilseed

The partitioning of seed yield (i.e., yield components) in camelina as a function of applied N was not investigated in this study. However, most of the increase in seed yield in canola attributable to N is due to increased number of siliques plant^{-1} (Hocking et al., 1997; Svečnjak and Rengel, 2006). Our visual observations suggest the same is true for camelina. These studies (Hocking et al., 1997; Svečnjak and Rengel, 2006) also reported that seed weight response to applied N in canola is variable and inconsistent.

Overall, this study shows that camelina is a viable spring oilseed crop for intermediate and higher precipitation areas of the inland PNW. Camelina production is also likely feasible in low precipitation areas of the inland PNW except during years of extreme drought. Yields in the Willamette Valley were lower than expected and camelina is likely not economical in this environment. Nitrogen needs of camelina per unit of yield and its NUE suggest it is productive and efficient spring oilseed crop from an agronomic perspective for the inland PNW.

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Table 1. Characteristics of study locations.

Location	Lat./Long./ Elevation m	Soil Classification	Average annual Precipitation mm	Average GDD (5 C base) January 1-August 1 1980-2010
Lind, WA	47° 0'6.72"N, 118°33'52.08"W 497	Shano silt loam, (coarse-silty, mixed, superactive, mesic Xeric Haplocambids)	242	1428
Pendleton, OR	45°43'12.42"N, 118°37'22.19"W 455	Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxerolls)	444	1524
Moscow ID/Pullman WA	46°43'28.07"N, 116°57'11.09"W 809	Palouse silt loam (fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls)	695	1109
Corvallis, OR	44°37'30.26"N, 123°12'54.39"W 70	Willamette silt loam (fine-silty, mixed, superactive, mesic Pachic Ultic Argixerolls)	1085	1424

Table 2. Planting dates, available soil nitrogen[1], crop year precipitation and previous crop at four locations.

Location	Year	Planting date	Pre-plant available N kg/ha	Pre-plant sulfur mg/Kg 0-30 cm	Annual crop year precipitation mm (Sep. 1-Aug. 31)	Annual growing season precipitation (Mar. 1-Aug 31)	Previous crop
Lind	2008	15 Mar	75	8	174	47	W. Wheat
	2009	1 Mar	75	6	215	105	W. Wheat
	2010	2 Mar	59	8	294	141	W. Wheat
Pendleton	2008	12 Mar	90	12	368	154	W. Wheat
	2009	19 Mar	107	11	416	210	W. Wheat
	2010	4 Mar	109	13	479	283	W. Wheat
Moscow	2008	26 Apr	99		660	228	S. Barley
Moscow	2009	21 Apr	82		760	353	S. Barley
Pullman	2010	16 Mar	47		795	387	W. Wheat
Corvallis	2008	18 Feb	77		1036	259	Perennial Ryegrass
	2009	20 Feb	72		776	264	W. Wheat
	2010	19 Feb	64		1168	435	Oat

[1] Soils were sample to the 1.2-m depth at Lind and Pendleton and to the 0.6-m depth at Moscow/Pullman and Corvallis.

Table 3. Camelina seed yields at four locations averaged over three years as affected by applied nitrogen and sulfur.

Location	Nitrogen rate	Sulfur rate	Seed yield	Oil content[3]
	------------kg ha^{-1} ------------			%
Lind[1]	0	0	688 a[2]	
	11	0	704 a	
	11	9	728 a	
	22	0	741 a	
	34	0	739 a	
	34	9	693 a	
	45	0	758 a	
	56	0	785 a	
Pendleton	0	0	1536 b	32.0
	17	0	1660 ab	32.9
	34	0	1673 ab	31.0
	50	0	1760 a	31.9
	50	11	1791 a	31.0
	67	0	1776 a	32.3
	84	0	1835 a	32.2
Moscow/Pullman	0	0	1129 f	37.2
	0	22	1152 f	34.3
	22	0	1338 e	32.6
	22	22	1384 e	34.2
	45	0	1661 d	38.4
	45	22	1700 d	34.5
	67	0	1913 bc	34.0
	67	22	1886 c	35.5
	90	0	2072 ab	35.1
	90	22	2095 ab	37.8
	112	0	2196 a	37.2
	112	22	2198 a	34.3
Corvallis	0	0	1219 c	34.0
	0	22	1386 bc	35.4
	22	0	1310 bc	32.3
	22	22	1389 bc	36.5
	45	0	1596 abc	32.7
	45	22	1564 abc	36.5
	67	0	1690 ab	33.8
	67	22	1759 ab	35.3
	90	0	1750 ab	33.3
	90	22	2009 a	36.2
	112	0	1915 a	30.7
	112	22	1952 a	35.3

[1] Only two years of seed yield data are available from Lind.

[2] Within-site seed yields followed by the same latter are not significantly different at $P < 0.05$.

3Within-site oil content was not significantly different at any of the four locations.

Table 4. Analysis of variance camelina seed yield at four sites over three years as affected by year, applied N, applied S.

	Location			
Source	Lind[1]	Pendleton	Moscow/Pullman	Corvallis
Year (Y)	**	*	***	***
N Rate (N)	NS	**	***	***
Sulfur (S)	NS	NS	NS	NS
NxS	NS	NA[2]	NS	NS
NxY	NS	NS	***	NS
SxY	NS	NS	NS	NS
NxSxY	NS	NA	NS	NS

* Significant at P< 0.05, ** Significant at P< 0.01, Significant at P< 0.001

[1] two years of seed yield data at Lind.

[2] Not applicable because of only one S rate at Pendleton, therefore the NxS interaction could not be analyzed.

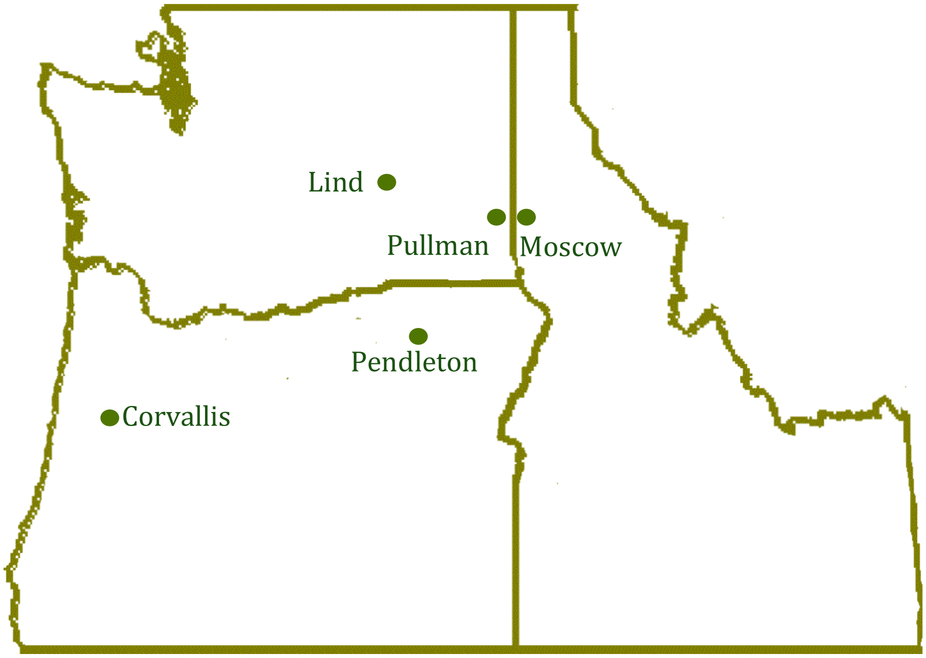

Fig. 1. Study site locations.

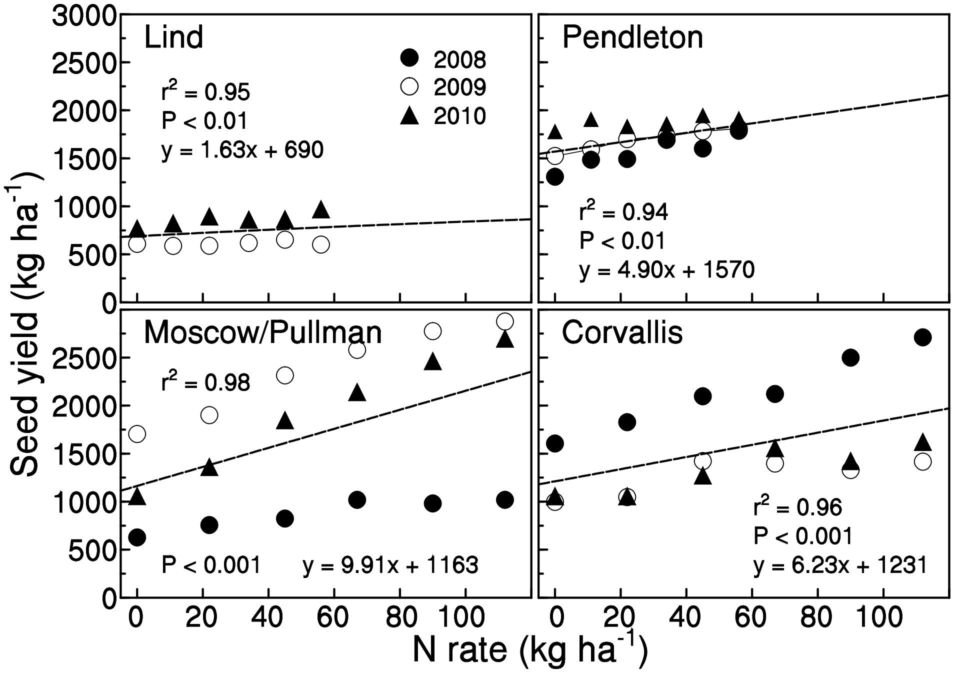

Fig. 2. Camelina seed yield response to applied nitrogen at four locations over three years.

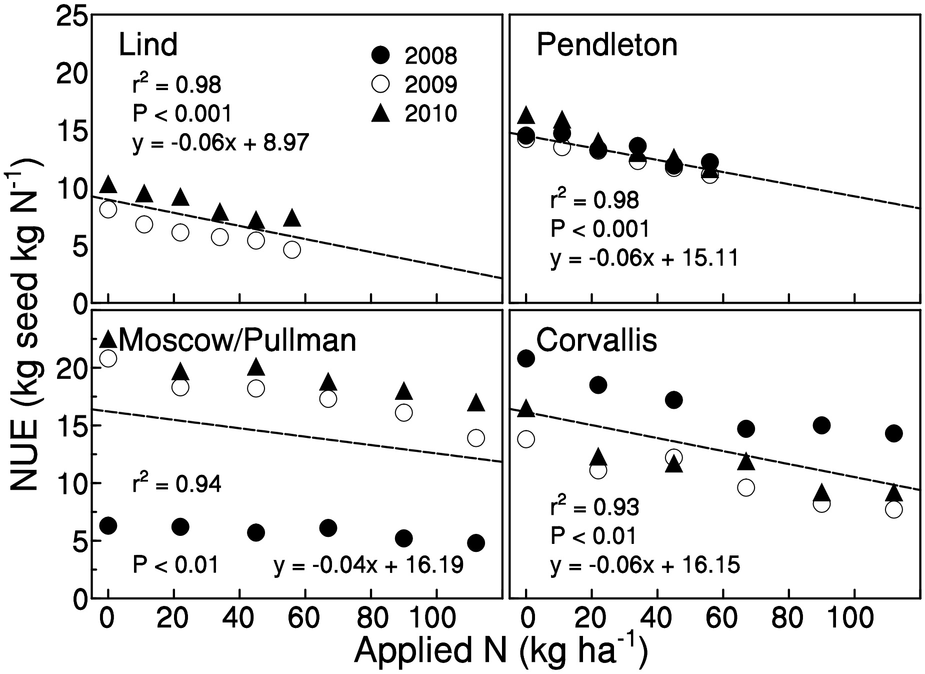

Fig. 3. Nitrogen use efficiency (NUE) of camelina grown at four locations over three years.