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RESEARCH

Canola and Camelina as New Crop Options for Cool-Season Production in California

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ABSTRACT

Annual crop production in California is mostly dominated by warm-season species that require irrigation. Irrigation has been restricted due to drought and policy and may become more uncertain due to climate change. To adapt to these changes, more cool-season crop options that require less water than summer annuals are needed. Wheat is the most common cool-season crop, and in other parts of the world canola (*Brassica napus* L.), and other Brassica oilseed species have diversified and improved the productivity and profitability of cereal-based agricultural systems. We evaluated multiple canola and camelina [*Camelina sativa* (L.) Crantz] varieties across diverse agro-ecological environments throughout California. Yield potential and viability of these oilseed species as complements to wheat were assessed. Canola achieved high mean yields and seed oil content, a very high yield potential, and showed only limited genotype × environment interaction. Using short-season spring-type varieties and suitable agronomic management, mean seed yields could be expected to reliably exceed 3000 kg/ha, with a mean seed oil content of 45%. Camelina yields were lower (1000 kg/ha with a mean seed oil content of 30%) and more variable than canola, and displayed high genotype × environment interactions and yield instability. Camelina did not mature earlier than the best yielding canola varieties. Camelina is not economically competitive with canola or wheat, but may be viable for specialized uses in California, especially in low rainfall locations, but this requires further investigation. Given these promising results, Brassica oilseed variety evaluation and agronomic studies should continue in California.

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Abbreviations: REML, Residual Estimated Maximum Likelihood method.

California has one of the most valuable and diverse agricultural industries in the world (FAOSTAT, 2015; Tolomeo et al., 2012), but annual cropping systems in the state are dominated by warm-season species that require irrigation. These systems tend to be high-value but water demanding, and face an increasing challenge from irrigation water supply constraints, which are expected to worsen with future climate change (Cayan et al., 2008; Cook et al., 2015; Jackson et al., 2012; Lee and Six, 2010; Mann and Gleick, 2015; Parry et al., 2007). Moreover, there has been a steady increase in the planted area of perennial crops such as almond [*Prunus dulcis* (Mill.) D.A. Webb] in California (USDA NASS, 2015), resulting in increasingly fixed demand for irrigation water for perennials, and correspondingly less irrigation water available for the production of annual warm-season species. Cool-season annual crops, that are produced during times of year with lower evapotranspiration demand, and that can make direct use of winter rainfall, provide less water-intensive cropping alternatives to maintain economic returns when water for irrigation is limited. In terms of planted area, cool-season cropping in California is dominated almost entirely by wheat (Tolomeo et al., 2012; USDA NASS, 2015). In other regions of the world, canola and other *Brassica* oilseed species have been

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used to diversify cereal-based agricultural systems (Booth and Gunstone, 2004).

There are compelling agro-economic reasons to consider brassicaceous oilseeds for diversifying cool-season cereal cropping. In a recent review of the subject, Angus et al. (2015) concluded that the diversification of wheat production systems with canola can have synergistic effects on overall system productivity, with canola benefiting subsequent wheat by acting as a disease break and suppressing weed growth, and by providing more flexibility in chemical weed control choices. Canola seed is utilized for the production of both edible oil and oilseed meal (which is used for livestock feed), and as a biofuel feedstock, and at present the demand for these products in the United States is considerably larger than domestic production (USDA ERS, 2014; FAOSTAT, 2015; Johnson and Fritsche, 2012; Newkirk, 2009; USDA NASS, 2015). More generally, increasing crop diversity can improve the viability of agricultural systems over time and provide agro-ecological benefits to the farming system (Janick, 1996;Janick and Whipkey, 2002; Lin, 2011). Knowles et al. (1981) made similar arguments for *Brassica* oilseed production in California nearly 35 yr ago. Despite this, commercial production of *Brassica* oilseeds in California is limited or nonexistent at the current time.

Previous evaluations of *Brassica* oilseeds in California have been conducted by several groups, including our own. Early work found moderate but variable yields, with problems due to uneven maturity and pod shattering (Cohen and Knowles, 1983; Knowles, 1980; Knowles et al., 1981). There has been progress in a variety of developments of *Brassica* oilseeds over the past 30 yr, notably for canola (Salisbury et al., 2016), and more recent work using improved varieties in California has found much higher yield potential (Kaffka et al., 2013). Previous research and development efforts supporting canola production in California focused on varieties and agronomic methods from other regions of North America, however, the production conditions of the state differ from canola growing regions elsewhere in North America, suggesting varieties and agronomic methods tested previously may not have been optimal. The range of agro-environments in California is broad, and includes lowland deserts, where irrigation is required, and continental climates where cool-season spring production is the norm, but most of the cropped area in California is similar climatically to other Mediterranean regions of the world (Grigg, 2002), and in particular to southern Australia where cool-season crops are grown primarily on natural rainfall. A research and development effort has supported the use of canola for the farming systems of southern Australia, and that region now sustains an extensive canola industry with more than 2 million hectares in production each year (ABARES, 2015). In southern Australia, spring-type canola varieties, which do not require vernalization to flower, are grown in winter rainfall dominant environments (Walton et al., 1999). The development of shorter-season varieties, which delay the onset of flowering long enough to produce a satisfactory leaf canopy to support high seed yield, but which flower and set seed prior to the onset of summer drought and heat stress, have been critical for successful canola production in that region (Salisbury et al., 2016; Walton et al., 1999). Given the climatic similarity between the two regions, canola variety development and production methodology from southern Australian is likely to have relevance for successful industry development in California.

Canola has received a greater global research and development effort than other brassicaceous oilseed species, and is therefore generally the highest yielding and best understood, but canola can become unreliable in low or more erratic rainfall conditions. Other oilseed species may yield more reliably under these circumstances and therefore be a better choice for growers (Francis and Campbell, 2003; Gunasekera et al., 2009; Hunt and Norton, 2011). Another oilseed species with potential as a new cool-season crop is camelina, a minor Brassicaceae crop originating from central Europe and central Asia. It is considered more cold and drought tolerant than canola (Allen et al., 2014; Cruz and Dierig, 2015; Francis and Campbell, 2003; Jiang, 2013; Putnam et al., 1993), and is also reported to have a shorter growing season (McVay and Lamb, 2008; Putnam et al., 1993). A literature search found that there is relatively little documented information available about the phenology or vernalization requirements of different camelina varieties. Currently, camelina oil is not used as a food oil for either humans or livestock, but it has been used for this in the past and there is recent research directed towards this use (Belancor et al., 2015; Campbell et al., 2013; Cruz and Dierig, 2015; Vollmann et al., 2007). Regulatory agencies in both the United States and Europe have recently approved camelina meal for use as livestock feed, although anti-nutritional components like glucosinolates are still a concern (Colombini et al., 2013).

The objective of the research described in this paper was to evaluate the performance of canola and camelina for the diversification of cool-season annual cropping systems in California. The seed and oil yields, and potential economic viability, of canola and camelina varieties across the diverse agro-environments of the state are discussed.

METHODS

Multi-Environment Trials

Variety Selection

A total of 48 canola and 105 camelina varieties were evaluated during the study (Tables 1 and 2). Phenological development of *Brassica* species is primarily altered by photoperiod and temperature, with a general shortening of phases as daylength and/or temperature increases, and in some species exposure to cool

Table 1. Canola varieties evaluated in a multi-environment study in California between 2012 and 2015 (arranged by source).

Source	Variety name	Maturity class	Herbicide tolerance
Cibus	C1511	Mid-late	
	V1	Mid	
	V2	Mid-late	
	V3	Mid-late	
DL Seed	DL5001	Early-Mid	Roundup Ready†
	DL5002	Early-Mid	Roundup Ready
	DL5003	Early	Clearfield
NPZ Australia	Agamax	Early-mid	
	AtomicHT	Early-mid	Triazine tolerant
	JardeeHT	Mid	Triazine tolerant
	TangoC	Early	
	TumbyHT(J+G)	Mid	Triazine tolerant
Pacific Seeds	H12317		
	H12318		
	H22816		
	H4722	Early	
	H92002		
	H92048		
	I4403	Early-mid	
	I6654	Early-mid	
	I8802		
	K9317	Early	Clearfield
	K9319	Early-mid	Clearfield
	M17072		
	M26120		
	M26126		
	M46652		
	M8534		Sulfonyl urea
	M95027		Sulfonyl urea
	M95168		Sulfonyl urea
	M95199		Sulfonyl urea
	T18096		
	T18097		Sulfonyl urea
	T2522	Early-mid	Triazine
	T98022	Mid	Triazine
	T98060	Early-mid	Triazine
Winfield	HyClass 930	Early	Roundup Ready
	HyClass 947	Mid	Roundup Ready
	HyClass 955	Mid	Roundup Ready
	HyClass 969	Mid	Roundup Ready
	HyClass 988	Late	Roundup Ready
Anonymous‡	Anon. 1 to 6	Late/semi-winter types	

† Roundup: glyphosate: glyphosate, N-(phosphonomethyl) glycine; Clearfield: imazamox: (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-(methoxymethl)-3-pyridinecarboxylic acid.; Sulfonyl urea: 1-(2-chlorophenyl)sulfonyl-3-(4-methoxy-6-methyl-1,3,5-triazin-2-yl)urea; Triazine: atrazine: 1-chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine.

‡ Anonymous: indicates that no permission was granted for varieties to be identified.

conditions (vernalization) will also induce or shorten the time to flowering (Robertson et al., 2002). Genotypes vary in their response to exposure to low temperatures but, very generally, a mean daily temperature of less than 5°C is effective for stimulating the transition from vegetative to reproductive growth phases (Hodgson, 1978; Robertson et al., 2002; Tommey and Evans, 1991). Throughout most of the agricultural regions of California, mean daily temperatures during the winter cropping season will therefore not be low enough for sufficient time to reliably vernalize winter-type canola varieties (CIMIS, 2015). The current study therefore focused on spring-type varieties with little-to-no vernalization requirements, and an emphasis was placed on shorter-season types, especially those adapted to southern Australia. A number of winter types were included in the multi-environment study as part of the broader research of the group, but all failed to flower and produce seed at any of the locations, and winter types were therefore excluded from subsequent trials and are not considered in the current paper. The canola varieties included both hybrid and open-pollinated lines, and lines with different herbicide tolerances and maturity classes. The camelina varieties had diverse backgrounds, and included both commercial and experimental lines, as well as wild accessions. Specific information regarding traits such as phenology or vernalization requirements was not available for the majority of the camelina varieties. Not all varieties of canola and camelina were included in every trial across years due to restrictions in land availability, variety availability in each year, and seed supply of each variety.

Location Selection

Sites throughout the main agricultural regions of California were selected for multi-environment trial locations (Fig. 1; Table 3), representing the range of soils and climates found where cool-season wheat is produced currently. These were judged to be the most likely environments for future canola and camelina production. Data regarding the planted area and distribution of cereal growing areas in California were obtained from the California Pesticide Use Reporting database (Pesticide Use Reporting Database, 2014). The reported cropping data were aggregated to "section" level or grids (240 ha or 1 square mile) that cover the entire state. The 10-yr mean precipitation data were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate mapping system website (PRISM Climate Group, 2004), and overlain with cropping region data using ArcGIS software.

Experimental Design, Establishment and Management

All locations in the Central Valley, Central Coast uplands, and Imperial Valley regions were planted in late autumn of each season. Locations were planted over three consecutive winter–spring seasons in 2012–2013, 2013–2014 and 2014–2015. The Tulelake location is too cold for winter cropping and instead supports early, cool-season, spring cereals, and was therefore planted in the spring of 2013, 2014, and 2015.

Canola and camelina were established in separate trials. Agronomic management of the trials was in accordance with accepted practices for canola and camelina in Australia and North America (Boyles et al., 2012; CCC, 2015; Duff et al., 2006; Enjalbert and Johnson, 2011; George et al., 2008; Hulbert et al., 2012; Lafferty et al., 2009; McCaffery et al., 2009; McVay and Lamb, 2008; Pritchard et al., 2010; Sharma et al., 2012; USCA, 2015). Trial design and data collection were in accordance with variety trial protocols of the Kansas State University

Table 2. Camelina varieties evaluated in a multi-environment study in California between 2012 and 2015 (arranged by source).

SusOils			Germplasm Resources Information Network USDA		
Variety name	Secondary variety name/s	Country of origin	Variety name	Secondary variety name/s	Country of origin
Blaine Creek		USA	PI 650142	CS-163-2073-72/Ames 26665/CS3	Denmark
Calena			PI 258366	VNIIMK 17	Former Soviet Union
CS117	CAM 164/STAMM 06X10A	Germany	PI 258367	Voronezh 349	Former Soviet Union
CS123	CAM 161/STAMM 10X15	Germany	PI 304268	No. 401	Sweden
CS14			PI 304269	No. 402	Sweden
CS141	CAM 147/STAMM 09X13	Germany	PI 304270	No. 403	Sweden
CS143	CAM 32	Soviet Union	PI 304271	No. 406	Sweden
CS144	CAM 34/Omskij	Soviet Union	PI 311735	Borowska	Poland
CS147	CAM 167/STAMM 06X14C	Germany	PI 311736	Pryzbrodzka/CS57	Poland
CS152	CAM 192/STAMM 06X13A	Germany	PI 597833	163-2073-72/CS1	Denmark
CS154	CAM 155/STAMM 08X13	Germany	PI 633192	CR 476/65/CS24	Germany
CS156	CAM 67 Hoga	Denmark	PI 633193	CR 492/94a	Germany
CS162	CAM 30/Zarja Socialisma	Former Soviet Union	PI 633194	Giessen no. 3	Germany
CS163	CAM 37/Zavolskij	Soviet Union	PI 650140	Came	Germany
CS168	CAM 174/VORONEZSKIJ 349		PI 650141	NU 52279	Minnesota
CS172	CAM 146/STAMM 13X14A	Germany	PI 650143	CS-CROO	Germany
CS178	CAM 124/PRFGL.22	Germany	PI 650144	Boha	Denmark
CS179	CAM 156/STAMM 09X15	Germany	PI 650145	BRSCHW 28347	Germany
CS184	CAM 201/STAMM 03X13	Germany	PI 650146	BRSCHW 30021	Sweden
CS189	CAM 223/BOROSKA IHAR		PI 650147	Came	Sweden
CS192	CAM 10/Voronezkij	Former Soviet Union	PI 650148	Giessen no. 3	Germany
CS2	DJ		PI 650149	Giessen no. 4	Germany
CS212	CAM 241/PRFGL.78	Germany	PI 650150	Hoga	Denmark
CS217	CAM 251/STAMM 05X14A	Germany	PI 650151	Svalof	Sweden
CS219	CAM 253/STAMM 06X14B	Germany	PI 650152	CPS-CAM23	Germany
CS221	CAM 254/STAMM 02X08A	Germany	PI 650153	CPS-CAM10/Ames 26676/CS11	Former Soviet Union
CS229	CAM 31	Poland	PI 650154	CSS-CAM25	Former Soviet Union
CS234	CAM 49	Poland	PI 650155	CSS-CAM27	Poland
CS235	CAM 77/ZARJA SOCIALISMA, AUSLESE 2	Former Soviet Union	PI 650156	CSS-CAM29/Ames 26679/CS13	Former Soviet Union
CS236	CAM 79/PRFGL.47	Germany	PI 650157	CSS-CAM30	Former Soviet Union
CS237	CAM 80/PRFGL.36	Germany	PI 650158	CSS-CAM31	Poland
CS238	CAM 83/PRFGL.75	Germany	PI 650159	CSS-CAM33	Poland
CS33	Celine	France	PI 650160	CSS-CAM34	Former Soviet Union
CS45	Ames 22986	Germany	PI 650161	CSS-CAM35	Former Soviet Union
CS5	Boha/Ames 26667	Denmark	PI 650162	CSS-CAM36	Poland
CS50	Ames 26678	Poland	PI 650163	CSS-CAM37	Former Soviet Union
CS60			PI 650164	CSS-CAM38	Austria
CS66			PI 650165	CSS-CAM7/Ames 26688/CS20	Former Soviet Union
CS68			PI 650166	CSS-CAM8/Ames 26689/CS21	Former Soviet Union
CS73			PI 650167	Index Seminum 144	Poland
CS74			PI 650168	NE2006-1	Nebraska
CS75			PI 652885	1	Slovenia
CS80			PI 652886	4	Slovenia
CS86	Robbie				California
CS9	CS-CR1675/Ames 26672				Germany, Mecklenbu
CS90	Stepovyi 1				Ukraine
CS91	Pretyzh				Ukraine
SO-30		USA			
SO-40		USA			
SO-50		USA			
SO-60		USA			
SOX_1843_22		USA			
SOX_1885_8		USA			
SOX_1999_20		USA			

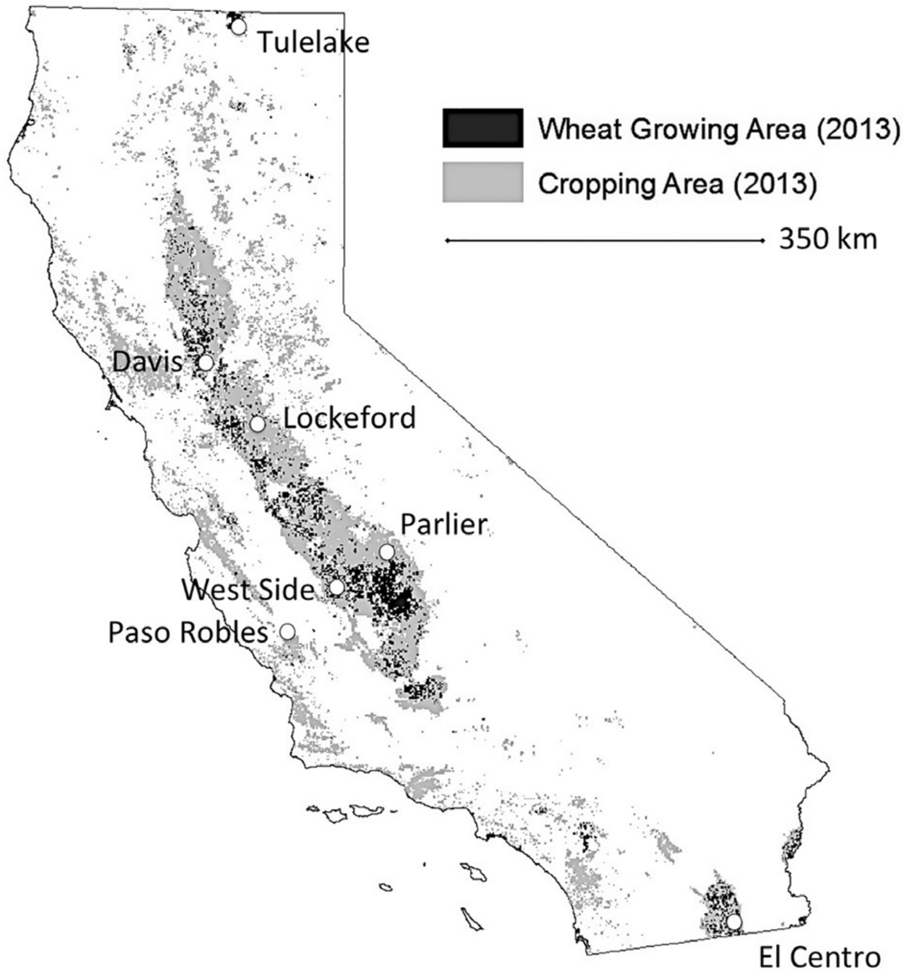

Fig. 1. Oilseed multi-environment trial locations used in this study. The figure also shows the winter cereal production regions of California and the cropping regions of the state.

Table 3. Details of the field trial locations used in the multi-environment study.

Location name	Abbre-viation	Location details	Irrigation	Lat.	Long.	Mean winter rainfall
						mm
Davis	D	UC Davis Campus Research Station	Irrigated	38.5	–121.8	469
El Centro	E	UC ANR Desert Research and Extension Center	Irrigated	32.8	–115.4	82
Lockeford	L	USDA Lockeford Plant Material Center	Irrigated	38.2	–121.7	313
Parlier	P	UC ANR Kearney Agricultural Research and Extension Center	Irrigated	36.6	–119.5	283
Paso Robles	PR	Private farm	Unirrigated	35.6	–120.7	361
Tulelake	T	UC ANR Intermountain Research and Extension Center	Irrigated	42.0	–121.5	288
West Side	WS	UC ANR West Side Research and Extension Center	Irrigated	36.3	–120.1	221

National Winter Canola Variety Trials and the Australia Crop Accreditation System (GRDC NVT, 2015; KSU, 2015).

Sites on research stations were sown following small-grain crops and the upland coastal locations followed fallow or pasture. Prior to sowing, sites were disked then harrowed to create a well-worked seedbed. If available, and considered necessary, pre-irrigation was used to encourage weed germination, and weeds were then controlled with either glyphosate [*N*-(phosphonomethyl)glycine] or by cultivation. Treflan 2 L/ha [trifluralin, 2,6-Dinitro-*N*,*N*-dipropyl-4-(trifluoromethyl) aniline] was applied pre-plant to the canola locations for further weed control. Treflan is not approved for use on camelina in California and was not used in camelina trials. Poast 2 L/ha (sethoxydim, 2[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one), and inter-row cultivation and hand weeding were used for post-emergent control of weeds. Some canola varieties had herbicide tolerance traits but these could not be utilized in this study due to the presence of non-herbicide tolerant varieties.

Water, physical and chemical properties of soils at the locations are summarized in Tables 4 and 5. At sowing, soil samples were taken from at least three locations in each field at depths of 0, 50, 100, and 150 cm using a soil corer. Samples were oven dried to determine volumetric soil moisture content

Table 4. Summary of the irrigation, precipitation, and soil physical and chemical properties at all the research locations used in this research.†

Location	Date planted	Previous rotation	Season	Irrigation		Precipitation	Estimated soil water content root zone above permanent wilting point	Seasonal plant available water		Bulk density	pH	Sand	Silt	Clay	Organic matter
				Camelina	Canola			Camelina	Canola						
				mm						g/cm³		%			
Davis	9 Nov. 2012	Cover crop	2012–2013	0	0	294	−46	248	248	1.4	7.4	39.0	28.5	32.5	2.0
Davis	15 Nov. 2013	Cover crop	2013–2014	360	360	219	26	605	605	1.5	6.8	46.0	29.0	25.0	1.9
Davis	20 Oct. 2014	Cover crop	2014–2015	230	230	361	141	732	732	1.6	7.2	49.5	27.0	23.5	1.7
El Centro	2 Oct. 2013	Cover crop	2013–2014	640	780	18	−66	592	732	1.4	8.0	7.0	34.5	58.8	1.8
El Centro	13 Nov. 2014	Cover crop	2014–2015	290	290	42	0	332	332	1.4	7.8	9.3	34.3	56.3	1.2
Lockeford	25 Nov. 2013	Pasture	2013–2014	10	10	180	265	455	455	1.6	6.9	43.5	39.0	17.5	1.8
Lockeford	23 Oct. 2014	Pasture	2014–2015	30	30	248	−14	264	264	1.6	7.4	62.5	23.5	14.0	1.2
Parlier	2 Dec. 2013	Cover crop	2013–2014	130	130	125	143	398	398	1.7	7.3	56.5	32.5	11.0	0.6
Parlier	27 Oct. 2014	Cover crop	2014–2015	130	130	149	137	416	416	1.7	7.1	69.0	21.0	10.0	0.5
Paso Robles	27 Nov. 2012	Fallow	2012–2013	0	0	182	−63	119	119	1.2	7.4	33.7	29.0	37.3	2.5
Paso Robles	11 Nov. 2013	Fallow	2013–2014	0	0	155	−133	22	22	1.1	7.7	29.3	35.0	35.7	2.5
Tulelake	9 May 2013	Cover crop	2013	10	10	201	170	381	381	0.7	6.9	41.0	36.0	23.8	4.0
Tulelake	13 May 2014	Cover crop	2014	230	350	252	178	660	780	0.7	7.3	52.0	28.5	19.5	5.2
Tulelake	2 June 2015	Cover crop	2015	280	310	143	69	492	522	0.7	7.2	36.0	30.5	33.5	4.3
West Side	28 Nov. 2012	Cover crop	2012–2013	40	40	99	−17	122	122	1.3	7.8	13.0	34.7	52.3	2.1
West Side	28 Oct. 2013	Cover crop	2013–2014	170	170	75	0	245	245	1.4	8.0	21.8	35.3	43.0	1.7
West Side	28 Oct. 2014	Cover crop	2014–2015	190	190	141	2	333	333	1.3	7.9	28.5	30.5	41.0	1.7

† Values at all locations are averages across all soil layers. Permanent wilting point is defined as the volumetric water content of the soil at a matric potential of −1.5 MPa.

and dry bulk density. Using volumetric soil moisture content and bulk density values the volumetric water content in the total soil profile (to a depth of 200 cm) was estimated. Chemical and physical analyses were then performed on the samples by A&L Western Laboratories (1331 Woodland Ave., Suite 1, Modesto, CA 95351). Using rainfall, irrigation, the estimated volumetric water content in the total soil profile, and the permanent wilting point (volumetric water content at −1.5 MPa), the seasonal plant available water was estimated for each location (Table 4).

Previous experience with oilseed variety trials in California has found that P, K, and S content in agricultural soils are generally not limiting, although additional P, K, and S were sometimes added as part of fertilizer blends available at individual research locations. Nitrogen was applied pre-plant at minimum rate of 50 kg/ha and additional N was applied as a spring top-dress. The total application rate of N applied as a top-dress was varied between locations and years depending on estimated needs of the crop given results of soil analyses and seasonal conditions (Table 5). Crops were not considered to be nutrient limited at any of the locations (Hulbert et al., 2012; Pritchard et al., 2010; Putnam et al., 1993; Solis et al., 2013; Wysocki et al., 2013).

A partially replicated, spatially optimized, design was used for each trial at each location (Coombes, 2009). The sowing window was between October and November for all locations except Tulelake. This planting window for *Brassica* in California was previously established by Knowles et al. (1981), and Kaffka et al. (2013), and is comparable to the seasonally-equivalent planting window for canola in southern Australia. Northeastern California (Tulelake) experiences a mild-summer, continental-type, climate with cold winters. The multi-environment trial location in that region was spring sown between May and June after the risk of late season frost had passed.

Both canola and camelina were direct-drilled using a cone-planter with double-disk openers at a row spacing of between 15 and 18 cm. Plot width varied from six to nine rows. Plot length varied, depending on land availability, from 5.5 to 8.5 m, with 30 cm spacing between plots. Canola was planted at a seeding rate of approximately 5 kg/ha and a depth of less than 2 cm (CCC, 2015). Camelina was planted at seeding rate of approximately 3 kg/ha and a depth of less than 2 cm (Lafferty et al., 2009; McVay and Lamb, 2008).

Where mean seasonal rainfall permitted an attempt was made to rely on rainfall to meet crop water needs, however abnormally dry conditions were experienced in all years of the project, therefore irrigation was used at some locations to ensure seedbed moisture was adequate for even germination and additional irrigation was applied if plants exhibited obvious moisture stress (i.e., early morning leaf wilting) during the growing season (Table 4). Irrigation was not available at the Paso Robles location.

Table 5. Summary of soil fertility and fertilization at all the research locations used in this work. Soil fertility samples taken following pre-plant fertilization.

Location name†	Year	Fertility at sowing: N NO_3	P Bray	P Olsen	K	S SO_4	Top dress fertilization, Canola: N	P	K	S	Camelina: N	P	K	S	Fertilizer type
		mg/kg					kg/ha								
Davis	2012–2013	9	5	6	181	11	140	0	0	0	140	0	0	0	Urea blend
Davis	2013–2014	21	12	9	189	7	110	0	0	60	70	0	0	50	Ammonium sulfate
Davis	2014–2015	9	7	9	197	14	200	100	110	40	200	100	110	40	Urea blend
El Centro	2013–2014	51	2	19	4	147	110	0	0	0	0	0	0	0	None
El Centro	2014–2015	9	7	22	313	495	200	30	40	30	200	30	40	30	Urea blend
Lockeford	2013–2014	14	44	19	95	10	50	0	0	0	30	0	0	0	Urea
Lockeford	2014–2015	5	51	34	117	19	160	20	0	30	160	20	0	30	Urea
Parlier	2013–2014	56	22	7	2	18	90	0	0	60	60	0	0	40	Ammonium sulfate
Parlier	2014–2015	34	30	31	65	12	200	50	40	40	200	50	40	40	Urea blend
Paso Robles	2012–2013	7	39	17	3	8	50	0	0	60	50	0	0	60	Ammonium sulfate/Urea
Paso Robles	2013–2014	12	10	6	2	7	110	0	0	110	50	0	0	50	Blend
Tulelake	2013	11	30	31	314	201	160	30	220	40	110	30	220	40	Blend
Tulelake	2014	32	27	45	218	38	160	30	220	40	110	30	220	40	Blend
Tulelake	2015	25	32	34	161	33	160	30	220	40	110	30	220	40	Blend
West side	2012–2013	22	7	6	366	48	100	0	0	0	50	0	0	0	Urea
West side	2013–2014	20	8	5	274	41	100	0	0	50	80	0	0	50	Urea blend
West side	2014–2015	7	7	10	235	56	210	50	50	70	210	50	50	70	Blend

† NOTE: Values at all locations are for the top 50 cm of the soil profile.

Weather data for the locations was obtained from the California Irrigation Management Information System (CIMIS, 2015), The National Climatic Data Center (NCDC, 2015), and in-field weather stations, located at each research location.

Harvest and Sample Analyses

The mean flowering date for all varieties at the sites, when approximately 50% of plots at a location had flowers visible, was qualitatively recorded (KSU, 2015). Sites were considered ready to harvest when the majority of plots threshed freely. The moisture content of bulked canola seed samples was approximately 10% or less at this time across all environments (determined using a Superpro Moisture Analyzer, Supertech Agroline ApS, Hestehaven 5, 5400 Bogense, Denmark). All plots within locations were harvested during 1 d, either by manual cutting and threshing, or by a Wintersteiger small plot combine. At harvest, plant height, as well as qualitative ratings of lodging, shattering, seedpod maturity and bird damage of individual plots were recorded. Harvested seed was sieved to remove excess chaff and weighed to obtain total plot seed yield. Seed yield was conservatively estimated based on total plot area plus an additional 30 cm on both plot length and width, corresponding to the distance between adjacent plots.

Seed oil content of canola was determined via Near Infrared Spectroscopy by DL Seeds (P.O. Box 2499, Morden, MB R6M 1C2). Estimation of oil content of camelina was conducted by the University of Idaho, using a single 12-g sample following the procedure outlined by Hammond (Hammond, 1991) using a Newport MKIIIA Nuclear Magnetic Resonance (NMR) Analyzer (Oxford Instruments Inc, Concord, MA). The NMR was calibrated with a single reference sample of the same species with known oil content and the sample analysis performed as described by Howard and Daun (1991).

Statistical Analyses

Data from the current study were analyzed as a multi-environment trial with a factor analytic model adjusted for spatial field trends using the ASReml-R program (Beeck et al., 2010; Burgueño et al., 2000; Butler et al., 2007; Cullis et al., 2010; Kelly et al., 2007; R Core Team, 2014). ASReml-R uses the Residual Estimated Maximum Likelihood (REML) method to estimate variance components in mixed linear models (Burgueño et al., 2000). When field variety trials are laid out in a rectangular array of rows and columns, spatial analysis can be performed to improve the precision of estimated variety effects and variety contrasts within sites (Burgueño et al., 2000). Factor analytic models within ASReml-R are then used to capture the variance structure of genotype × environment effects, and can do so reliably in the context of unbalanced trial data (Beeck et al., 2010; Cullis et al., 2010). Varieties were analyzed as random effects and the best linear unbiased predictors (BLUP) of the variety effects were used as estimates of the future performance of the varieties (Burgueño et al., 2000; Smith et al., 2005). The optimal linear mixed model for each species was chosen based on the model selection process described by Zuur et al. (2009). Cullis et al. (2010) recommend a number of graphical displays as tools for interpreting the pattern of genotype × environment effects from this type of analysis. The relative differences in the ranking of the varieties between environments (genetic correlation) are visualized using a heat map, with the order of the environments (location × year combinations) based on an agglomerative (nested) hierarchical clustering algorithm that is implemented in the *agnes* package of R (Cullis et al., 2010). For additional details regarding the analytical methodology please refer to Cullis et al. (2010).

Crop yield in a given environment can be explained in terms of the resources available in that environment to support growth and yield and the biological and physical hazards that limit attainment of the yield potential (Bidinger et al., 1996). To investigate the relationship between environments in terms of environmental factors, data regarding edaphic variables (bulk density, soil texture, organic matter, pH, and fertility) and climatic variables (absolute maximum and minimum temperature, average mean temperature, and seasonal plant available water) were normalized then analyzed with the base principle component analysis function in R (R Core Team, 2014), with additional data visualization using the *ggplot2* package (Wickham, 2009). Exploratory analysis of the correlation between yields and the measured environmental variables was performed with the *PerformanceAnalytics* package in R (Peterson and Carl, 2014).

RESULTS

Field Trial Outcomes

Lower than average winter rainfall was experienced across California throughout the 3-yr trial period, but particularly in the second and third seasons (Tables 3 and 4). Canola at locations in the Central Valley (Davis, Lockeford, Parlier, Westside), Central Coast (Paso Robles), and Imperial Valley (El Centro) began flowering between February and March, and the camelina began flowering approximately a month earlier in January. No obvious problems from late season frost during flowering and pod-fill were observed at any locations or years. At all locations, the camelina and the majority of the canola varieties matured evenly both between and within individual varieties, with minimal shattering observed. Maturation time across all varieties within individual locations was very similar for both canola and camelina (Table 6).

Varieties of both species exhibited a range of heights and late-season lodging potentials, although lodging did not usually prevent harvesting. Exploratory analyses found only weak or unclear relationships between factors such as height, planting date, lodging, and subsequent seed yield. The extent of lodging was a qualitatively rated trait, making it problematic to statistically analyze, therefore these variables were not considered in the subsequent investigation of crop performance in this paper and the data is not presented.

Species Performance

Early- and mid-season spring canola varieties were consistently the best performing entries (Table 1; Fig. 2). Variety mean yields varied from approximately 1500 to 3000 kg/ha, and seed oil content from 40 to 48% (Fig. 2). Seed yield and oil content were less variable among camelina varieties, compared to canola (Fig. 2 and 3). The highest yielding lines of camelina included both named varieties and landraces, mean seed yield varied from 900 to 1100 kg/ha, and oil content from 29.5 to 30.5%. The standard error of estimation for camelina was greater than for the canola. Total oil yield was strongly correlated with seed yield for both canola and camelina (R^2 = 0.9 and 0.8, respectively) and estimated mean oil yield for the top ten varieties was approximately 1200 L/ha for canola and 360 L/ha for camelina. A summary of seed yield for each environment is presented in Table 7. A summary of the 10 highest-yield varieties of canola is also presented to provide an indication of possible yields given the selection of well-adapted varieties, those most likely to be chosen by growers. Exploratory correlation analysis found higher mean yields in canola were associated with greater seasonal available water (R^2 = 0.75, $p < 0.01$) and coarser texture soils (R^2 = 0.49, $p < 0.05$). No single factor was obviously correlated with higher yield in camelina (Tables 3 and 5).

Table 6. Planting and harvest dates, and days to harvest, for each of the canola and camelina variety trial locations used in this research.

Location name	Date planted	Date harvested	Days to harvest
Camelina			
Davis	9 Nov. 2012	8 May 2013	180
Davis	15 Nov. 2013	19 May 2014	185
Davis	29 Oct.2014	11 May 2015	203
El Centro	2 Oct. 2013	12 Mar. 2014	161
El Centro	13 Nov.2014	14 Apr. 2015	152
Lockeford	25 Nov. 2013	12 June 2014	199
Lockeford	23 Oct. 2014	19 May 2015	208
Parlier	2 Dec. 2013	22 May 2014	171
Parlier	27 Oct. 2014	5 May 2015	190
Paso Robles	27 Nov. 2012	7 May 2013	161
Paso Robles	11 Nov. 2013	10 June 2014	211
Tulelake	9 May 2013	2 Aug. 2, 2013	85
Tulelake	13 May 2014	12 Sept. 2014	122
Tulelake	2 June 2015	10 Sept. 2015	100
West Side	28 Nov. 2012	6 May 2013	159
West Side	28 Oct. 2013	1 May 2014	185
West Side	28 Oct. 2014	13 May 2015	197
		Mean (SD)	169(37)
Canola			
Davis	9 Nov. 2012	15 May 2013	187
Davis	15 Nov. 2013	29 May 2014	195
Davis	20 Oct. 22014	11 May 2015	203
El Centro	2 Oct. 2013	1 Apr. 2014	181
El Centro	13 Nov. 2014	14 Apr. 2015	152
Parlier	2 Dec. 2013	22 May 2014	171
Tulelake	9 May 2013	29 Aug. 2013	112
Tulelake	13 May 2014	12 Sept. 2014	122
Tulelake	2 June 2015	3 Sept. 2015	93
West Side	28 Nov. 2012	16 May 2013	169
West Side	28 Oct. 2013	15 May 2014	199
West Side	28 Oct. 2014	7 May 2015	191
		Mean (SD)	165(37)

The REML-based analyses found that the genotype and environment had a highly significant effect on yield for both species ($p < 0.01$). The heat-maps and dendrograms provide a convenient way to visualize differences in variety rankings between test environments to test

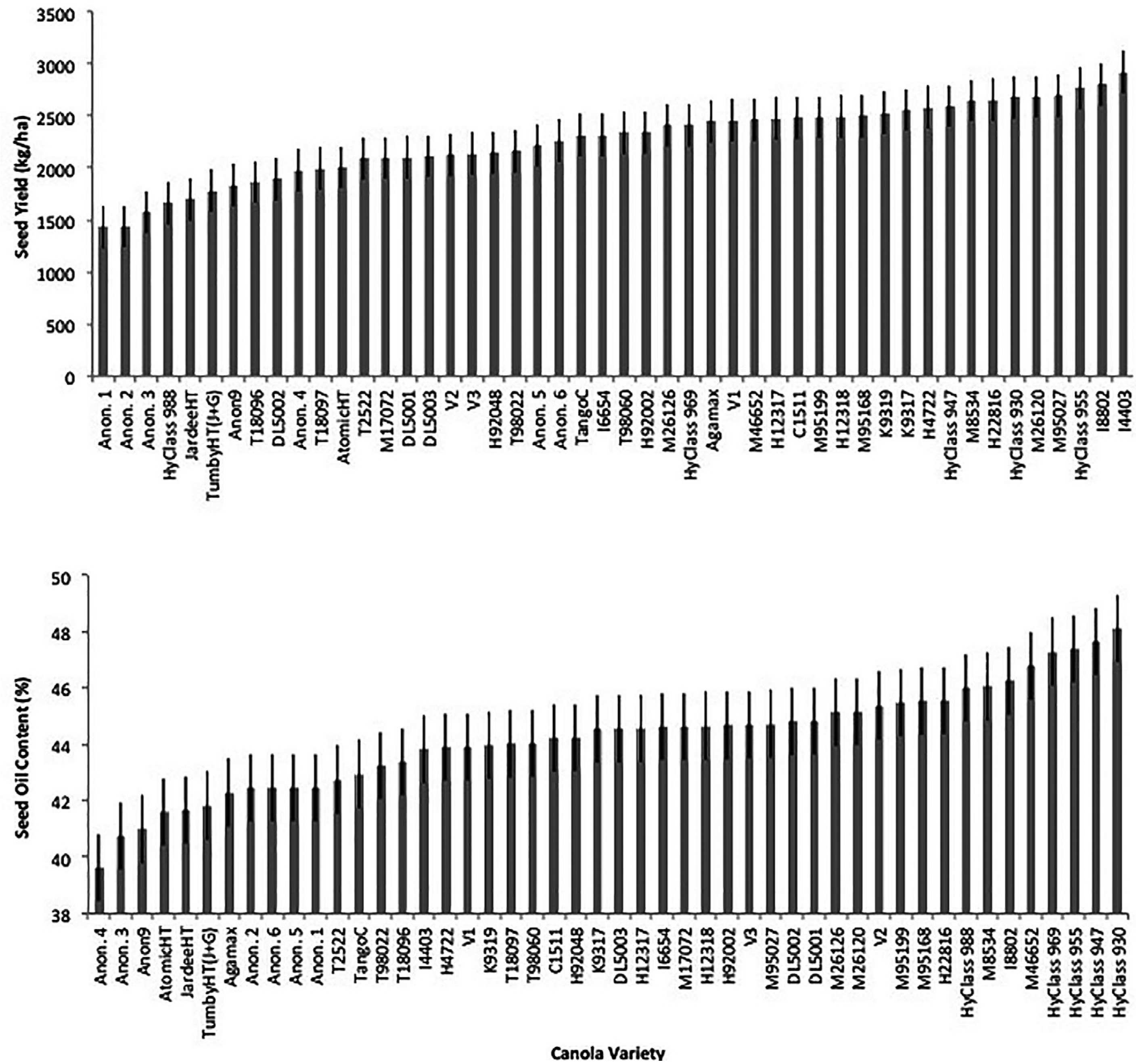

Fig. 2. The estimated mean yield and seed oil content of canola varieties from multi-environment trials (BLUPs). Error bars show standard error of estimation from the linear mixed model.

for genotype × environment effects (Fig. 4–7). Correlation between the environments can be interpreted as the extent of similarity in variety rankings, with negative correlations indicative of crossover genotype × environment interaction. For canola, there were two groups of environments for yield, although the corresponding clusters in the dendrogram formed above a genetic dissimilarity of approximately 0.6 (on a 0–1.0 scale), which may not be meaningful (Cullis et al., 2010), suggesting low crossover type genotype × environment effects. The analysis indicates slight clustering and lower genetic correlation in the second factor for seed yield (Fig. 4 and 6), but genetic dissimilarity for clusters was low (<0.6; Fig. 4) also suggesting low crossover type genotype × environment effects. High genetic correlations were seen across all environments for seed oil content, and the majority of the genetic variance occurred in the first factor (Fig. 4). In contrast to canola, low levels of genetic correlation between some environments, and clustering of the environments, were found for both seed yield and oil content in camelina (Fig. 5 and 7). Using a genetic dissimilarity of 0.6 as an approximate cutoff a number of clusters for both the seed yield and seed oil content of camelina are apparent (Fig. 7).

A principle competent analysis of the measured edaphic variables found that locations exhibited clear separation and clustering (Fig. 8). The West Side and El Centro locations

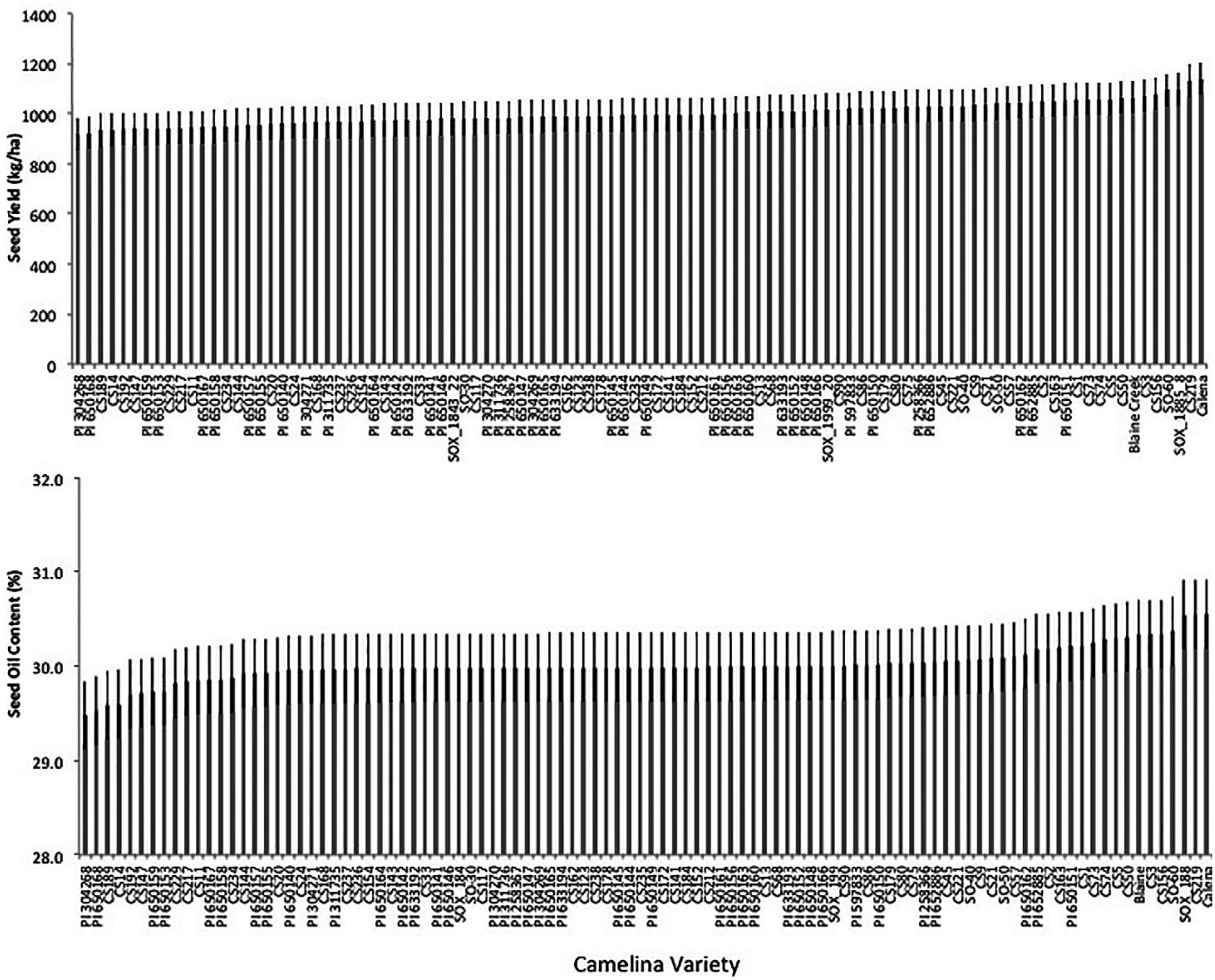

Fig. 3. The estimated mean yield and seed oil content of camelina varieties from multi-environment trial (BLUPs). Error bars show standard error of estimation from the linear mixed model.

were characterized by clay soils with high pH, Lockeford and Parlier by sandy soils and higher phosphorous, Tulelake by high organic matter and very low bulk density, and relative to all the locations Davis and Paso Robles were more average in terms of the measured edaphic variables. The analysis of climatic and seasonal water supply variables showed separation of the environments but no meaningful clustering, except for environments clustered near the origin of the vectors (Fig. 8). The clustering of the environments observed for yield and oil for yield of camelina seen in Fig. 7 is not clearly associated with the clustering and separation of environments in Fig. 8.

Given the generally high genetic correlations across environments for yield and oil content in canola (Table 8), BLUPs combining all environments are likely to provide good estimates of future variety performance and a reasonable basis for recommendations. Limited genetic correlation across environments in camelina (Table 9) suggests inconsistent performance from location to location and from year to year. Estimating BLUPs across all environments is therefore less meaningful, but given uncertainty about the underlying reason or reasons for the genotype × environment effects for camelina (see Discussion) BLUPs were still generated across all environments.

DISCUSSION

In this study, the oilseed species canola and camelina were evaluated as cool-season crops in multi-environment trials across a diverse range of environments throughout the agricultural regions of California.

Canola

This study suggests that with appropriate variety selection and management mean seed yields of 3000 kg/ha could be expected for canola when grown as a cool-season crop throughout most of California. At the Davis location in

Table 7. A summary of the yield performance of canola and camelina varieties across all locations and years.

Location	Harvest year	Environment code	Varieties included in the analysis	Location mean yield	SD	Maximum yield	Minimum yield	Yield of top 10 varieties
				kg/ha		—— kg/ha ——		
Canola								
Davis	2013	D13	27	2442	547	3640	1076	3055
Davis	2014	D14	78	3720	720	5021	1946	4586
Davis	2015	D15	46	3705	581	4737	2378	4380
El Centro	2014	E14	35	1281	947	3225	0	2379
El Centro	2015	E15	44	734	141	985	407	901
Parlier	2014	P14	74	3025	325	3761	2331	3378
Tulelake	2013	T13	26	1105	303	1542	342	1446
Tulelake	2014	T14	46	1815	524	2600	459	2351
Tulelake	2015	T15	44	4036	218	4427	3528	4296
West Side	2013	WS13	27	2083	322	2730	1361	2447
West Side	2014	WS14	53	1252	293	1821	521	1518
West Side	2015	WS15	45	1967	264	2540	1098	2128
Camelina								
Davis	2013	D13	8	1469	60	1664	1335	1573
Davis	2014	D14	62	706	67	964	489	769
Davis	2015	D15	96	849	69	1071	673	944
El Centro	2014	E14	9	1118	158	1627	760	1390
El Centro	2015	E15	96	333	103	655	126	456
Lockeford	2014	L14	32	1043	118	1531	758	1235
Lockeford	2015	L15	54	876	34	981	771	912
Parlier	2014	P14	32	954	133	1361	633	1177
Parlier	2015	P15	96	802	70	1028	642	920
Paso Robles	2013	PR13	8	290	38	413	205	354
Paso Robles	2014	PR14	32	296	41	421	115	285
Tulelake	2013	T13	8	1052	252	1929	269	687
Tulelake	2014	T14	32	1411	112	1734	1042	1515
Tulelake	2015	T15	54	2691	217	3427	1966	2973
West Side	2013	WS13	8	1978	50	2257	1668	2015
West Side	2014	WS14	32	286	37	446	189	328
West Side	2015	WS15	54	805	139	1275	471	1036

2014 one variety achieved a mean yield of 5000 kg/ha, which demonstrates the high yield potential of canola in the region. The oil content of these varieties could also be expected to reliably exceed the 42% commercial benchmark for canola (McCaffery et al., 2009). Growing conditions were not optimal during the study period, due to a multi-year drought, and there was a lack of clarity about locally optimal agronomic management under these conditions, so given best management practices and/or average rainfall levels, higher mean yields are predicted.

Mean yields and seed oil content observed in these trials for canola are higher than earlier field evaluations conducted in California in the late 1970s and early 1980s, and problems from shattering and uneven maturity reported in earlier work were not observed in the current study. This most likely reflects variety improvements that have occurred in canola since the earlier field trials were conducted (Salisbury et al., 2016). The mean yields observed in the current trials are also higher than mean yields of mostly dry-farmed canola elsewhere in the United States and Australia, which are usually between 1400 and 2000 kg/ha (George et al., 2012; GRDC NVT, 2015; USDA NASS, 2015).

The hypothesis that the most productive Australian varieties should be better adapted, in terms of yield and oil content, to California than North American varieties was partially supported. Many of the best performing varieties were short-season spring types developed in Australia, but some Australian varieties also yielded comparatively poorly. Some of these were very early flowering and some were triazine tolerant, both of which contribute to low relative yield potential under high yield potential conditions. Triazine herbicides cannot be used in California in any case. Some broadly adapted spring types developed for North America exhibited consistently high yields and ranked highly over all. Results do support the hypothesis that shorter-season spring-type canola varieties, in contrast to longer-season types, are likely to be well adapted

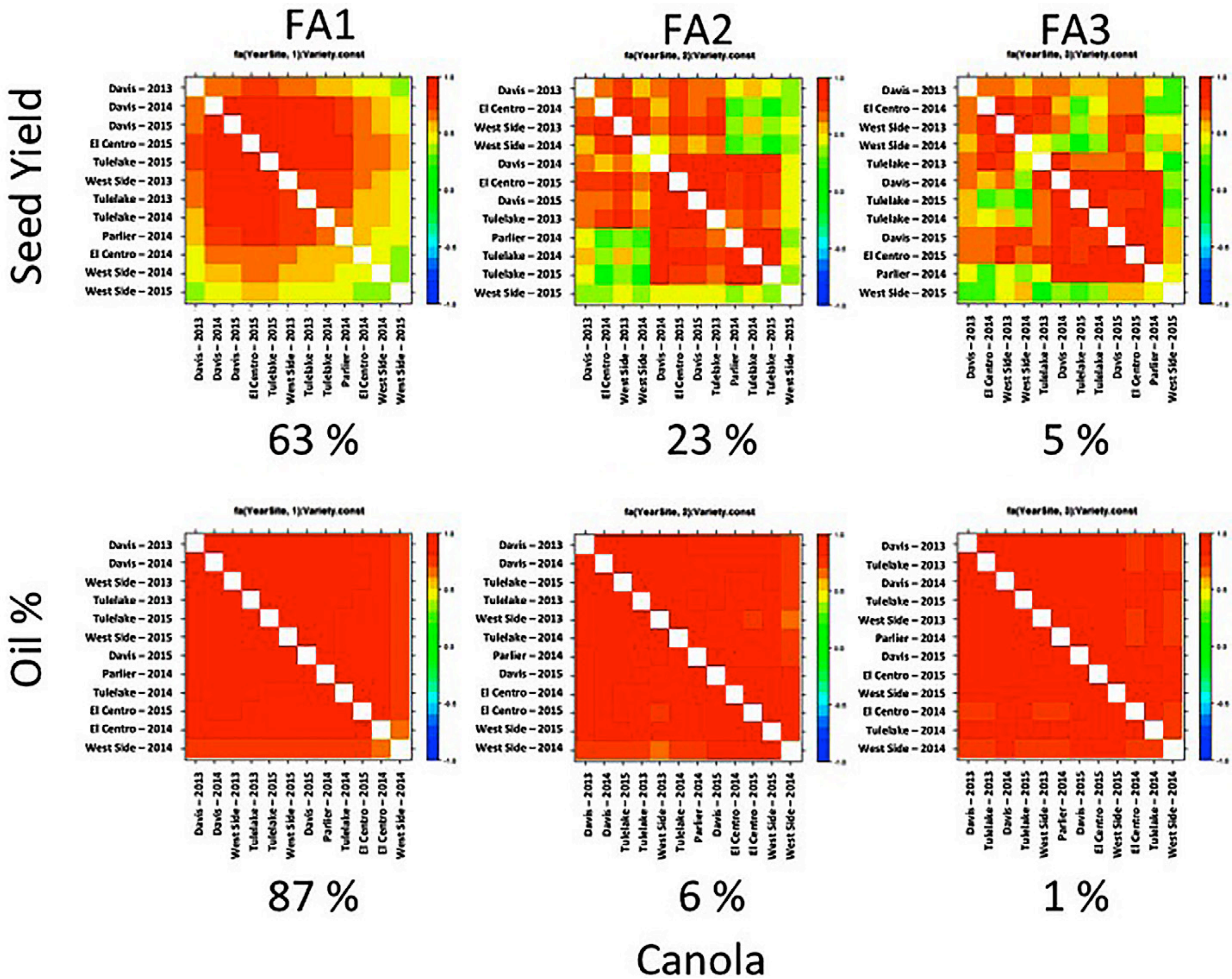

Fig. 4. Heat maps of the Residual Estimated Maximum Likelihood (REML) estimates of genetic correlation between environments for seed yield and seed oil content of canola in California. The proportion of genetic variance explained by the factor analysis is indicated. The key on the right hand side depicts the correlation color scale (red – high correlation, green – no correlation, blue – negative correlation). Environments are ordered as per the correspondence dendrograms in Fig. 6 based on an agglomerative (nested) hierarchical clustering algorithm.

to California because their phenology will match environmental conditions prevailing across much of the region during the cool-season production period. That is, they will delay the onset of flowering long enough to produce a satisfactory leaf canopy, but still flower and set seed prior to the onset of excessive heat and moisture stress that occurs typically in late May or June. Given these findings, ongoing evaluation of canola in California should emphasize shorter-season spring types, regardless of origin.

The high genetic correlation and low levels of clustering among the canola varieties suggests little or no meaningful crossover-type genotype × environment interaction occurred in the multi-environment trial, and therefore mostly consistent ranking of varieties across environments with respect to yield and seed oil content. This is despite the wide range of agro-environmental conditions between the trial locations, ranging from arid low desert, to Mediterranean areas, to one location with a cool continental climate. The germplasm tested in this study, although from diverse sources, was from commercial breeding programs, so it is likely that the majority of the varieties had been selected for broad adaptation and yield stability. The limited genotype × environment effects also suggest both that the yield estimates represent reliable predictions of yield for the varieties, and that future canola research and development in California can be conducted at a more restricted number of locations and still provide data that is likely to be broadly representative of canola performance across the state.

Camelina

Camelina yields were lower and more uniform across varieties than canola, averaging around 1000 kg/ha. These yields are comparable to mean yields observed for

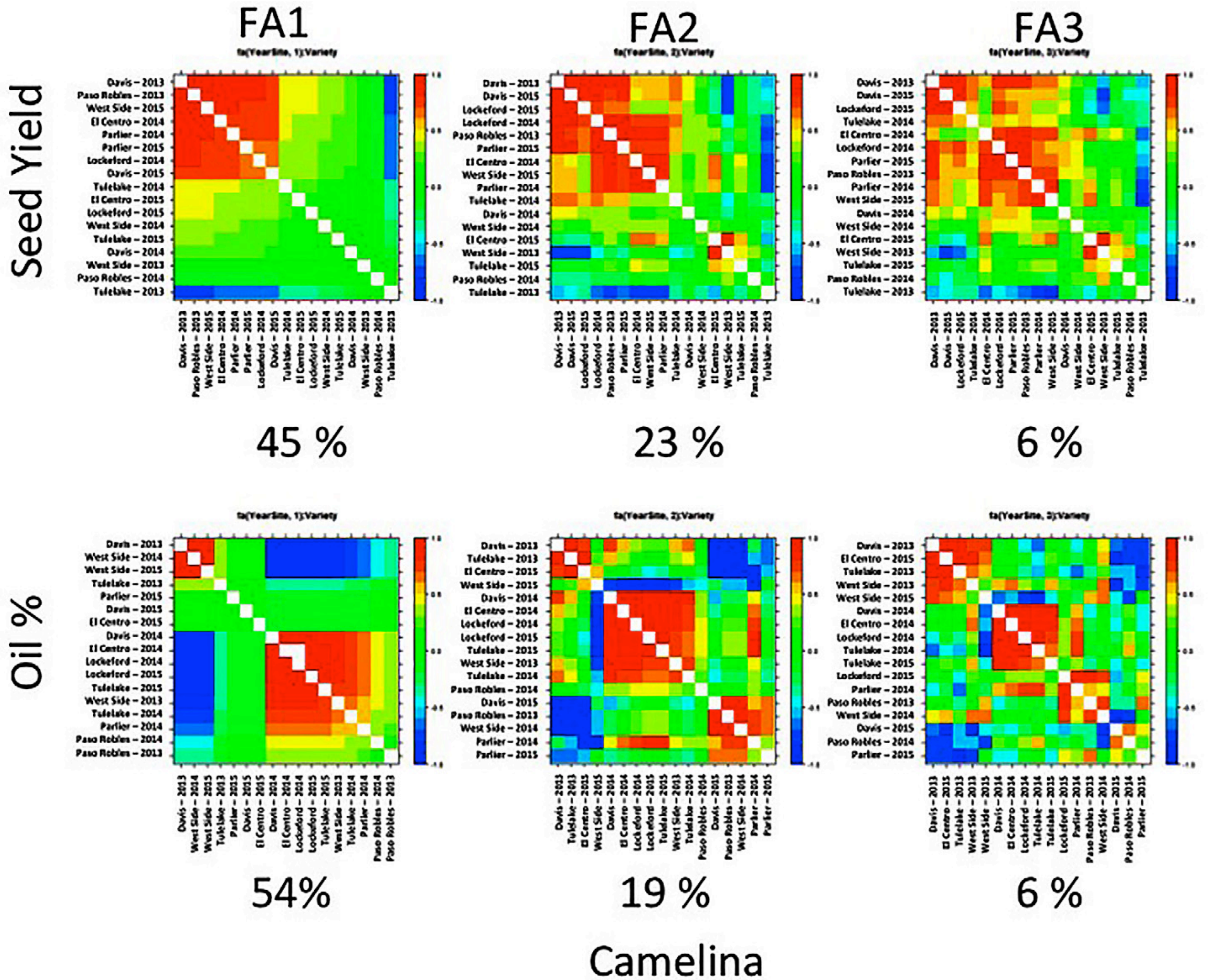

Fig. 5. Heat maps of the Residual Estimated Maximum Likelihood (REML) estimates of genetic correlation between environments for seed yield and seed oil content of camelina in California. The proportion of genetic variance explained by the factor analysis is indicated. The key on the right hand side depicts the correlation color scale (red – high correlation, green – no correlation, blue – negative correlation). Location-years are ordered as per the corresponding dendrograms in Fig. 7 based on an agglomerative (nested) hierarchical clustering algorithm.

camelina in both North America and climatically comparable regions of Australia (Campbell et al., 2013; McVay and Lamb, 2008; Pavlista et al., 2011; Putnam et al., 1993). One variety, however, achieved a mean yield of more than 3000 kg/ha at the Tulelake location in 2015, and another achieved 2300 kg/ha at the WSREC location, suggesting the species may have high yield potential. Additional variety development and testing, and agronomic research, are therefore warranted.

The low, often negative, genetic correlations among varieties across environments for yield and oil content suggest that significant crossover-type genotype × environment interaction is occurring for both traits. Significant clustering of environments was present in the ASReml-R analysis, although it was not related to specific locations, groups of locations or seasons, which is interpreted as significant genotype × location × year effects and instability. The clustering and separation of the environments was also not consistent with the clustering of the environments in the principle components analysis, so the reason for the genotype × environment patterns remains unexplained. Cryptic genotype × environment interaction, notably due to genotype × year effects, has been reported for camelina by other workers (Guy et al., 2014). Every environmental factor has the potential to cause relative differences in the performance of crop varieties (Fehr, 1987), and it is common that genotype × environment effects are identified only statistically without the underlying reason being understood (DeLacy et al., 1996).

It is hypothesized that the potential genotype × location × year effects and instability observed in the camelina reflect the comparative lack of variety development that

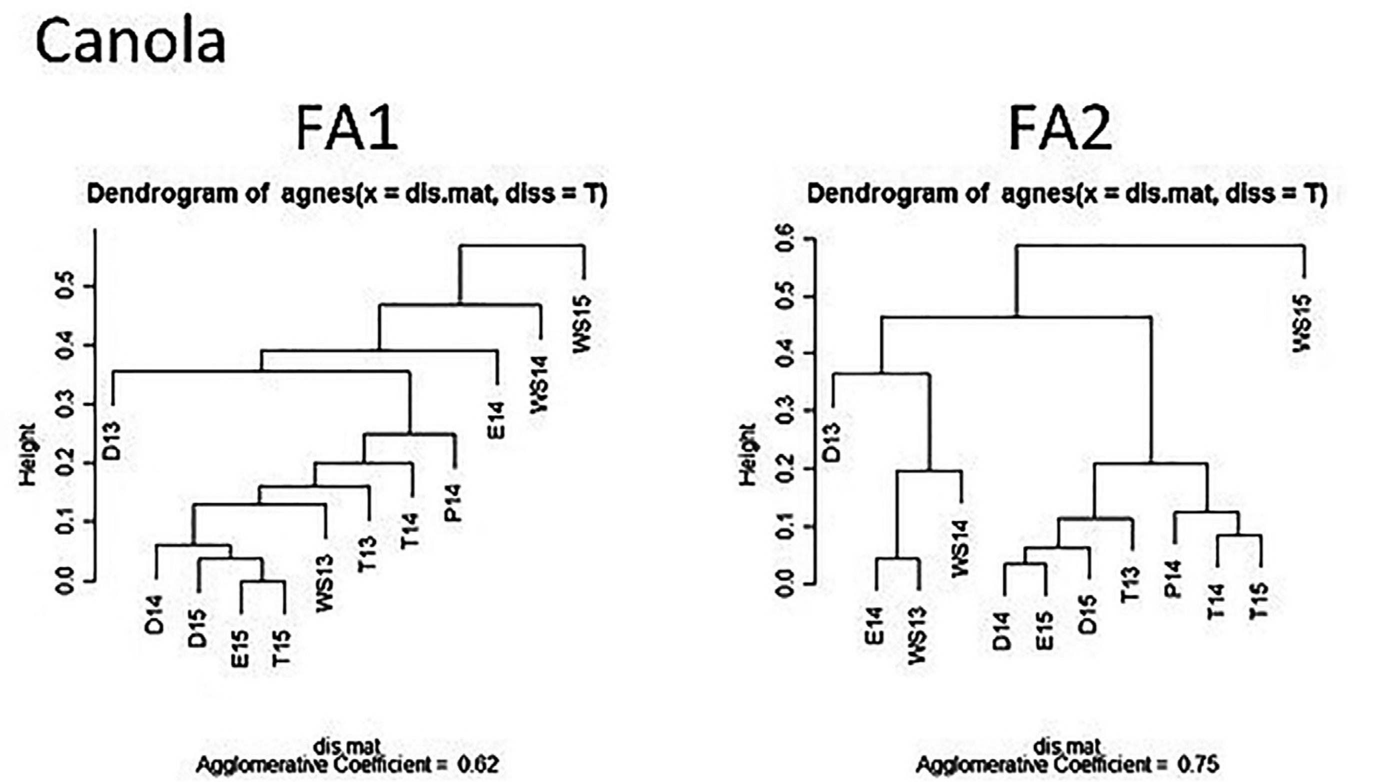

Fig. 6. Dendrograms of the dissimilarity matrix from agglomerative (nested) hierarchical cluster analysis of seed yield of canola (environment code as per Table 9).

has taken place relative to canola. Detailed information regarding the camelina varieties was not available, but unlike the majority of the canola varieties, only around 10% of the camelina varieties were named cultivars. The remainder of the varieties were a mixture of wild accessions, land races, or early generation offspring from breeding programs. It is therefore likely that most of the varieties have not been subjected to selection for either broad adaptation or stability, making it probable they would exhibit strong genotype × environment when exposed to the wide range of environmental conditions sampled in this study. Ongoing variety evaluation and agronomic testing of camelina in California will therefore need to be conducted across multiple locations and years to adequately capture these effects and characterize the crop's potential performance.

The cryptic genotype × environment interaction observed here makes summarizing the performance of the camelina varieties challenging. A single yield estimate across all environments for the varieties is presented, but is less precise than the similar value reported for the canola. Variety recommendations are therefore problematic. To minimize risk when producing a crop like camelina, that is likely to display significant genotype × location × year effects and instability, it is recommended that growers plant multiple varieties (Fehr, 1987).

Camelina is considered to be a shorter-season crop than canola (McVay and Lamb, 2008; Putnam et al., 1993), but across all locations and years in this work the mean days to harvest were very similar for both species. This may be because the canola varieties were also primarily short-season types, but other workers have found similar days to maturity for both species (Pavlista et al., 2011). Camelina may therefore not provide a meaningfully shorter rotational option than canola in some environments. Camelina was however observed to display greater resilience to drought and cold than canola, with some trials surviving to harvest when canola at the same location failed due to apparent lack of water or cold. The species may therefore represent a more reliable crop option when planting in expectation of colder temperatures at establishment or during a growing seasons with lower temperatures and less available soil moisture than required for canola (George et al., 2016).

Economic Viability

The economic viability of canola relative to winter wheat in California is uncertain given the immaturity of local seed markets. Winans et al. (2016) conducted an economic analysis of canola in California using the Bioenergy Crop Adoption Model (BCAM). BCAM is a partial mathematical programming (PMP) optimization model used to assess entry price and regionalized land allocation potential for new crops in California compared to incumbent land uses (Kaffka and Jenner, 2011; Kaffka et al., 2014). The model excludes land planted to perennial crops, under the

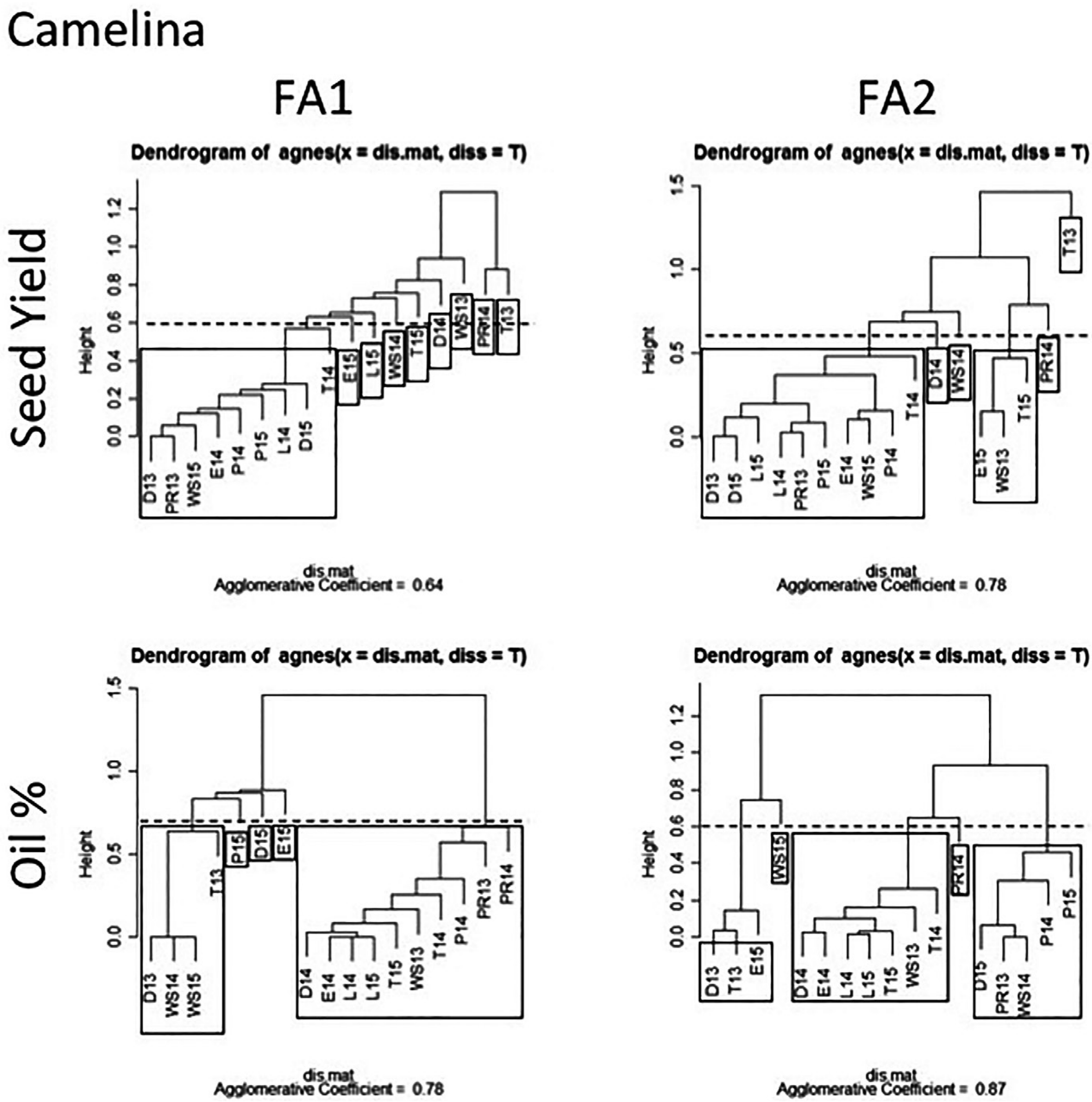

Fig. 7. Dendrograms of dissimilarity matrix from agglomerative (nested) hierarchical cluster analysis of seed yield and seed oil content of camelina (environment code as per Table 9). Putative clusters shown for branching above a genetic dissimilarity of 0.6 (Cullis et al., 2010).

assumption that such areas are not frequently rotated to new annual crops in response to small changes in crop prices. The analysis found that canola would be economically competitive with wheat at a seed price of more than US$480 per tonne, using prices observed and adjusted for 2012 (the year chosen for analysis), at seed yields at or greater than 3000 kg/ha. Relative prices are expected to vary from year to year but given the yields observed in the current study, and the conclusions of this economic analysis, canola could be a viable economic complement with wheat in California (USDA NASS, 2015; Winans et al., 2016). Given current seed markets, and at current yields and seed prices, camelina is not likely to be directly economically competitive with either wheat or canola (Kaffka and Jenner, 2011; Kaffka et al., 2014), although there may be other niches in the state where it could be a viable choice for growers.

CONCLUSIONS

The aim of this research was to evaluate and compare the viability of canola and camelina as new oilseed crops to support diversification of cool-season, cereal-dominated, farming systems in California. Canola achieved high mean yields and displayed a high yield potential. Using

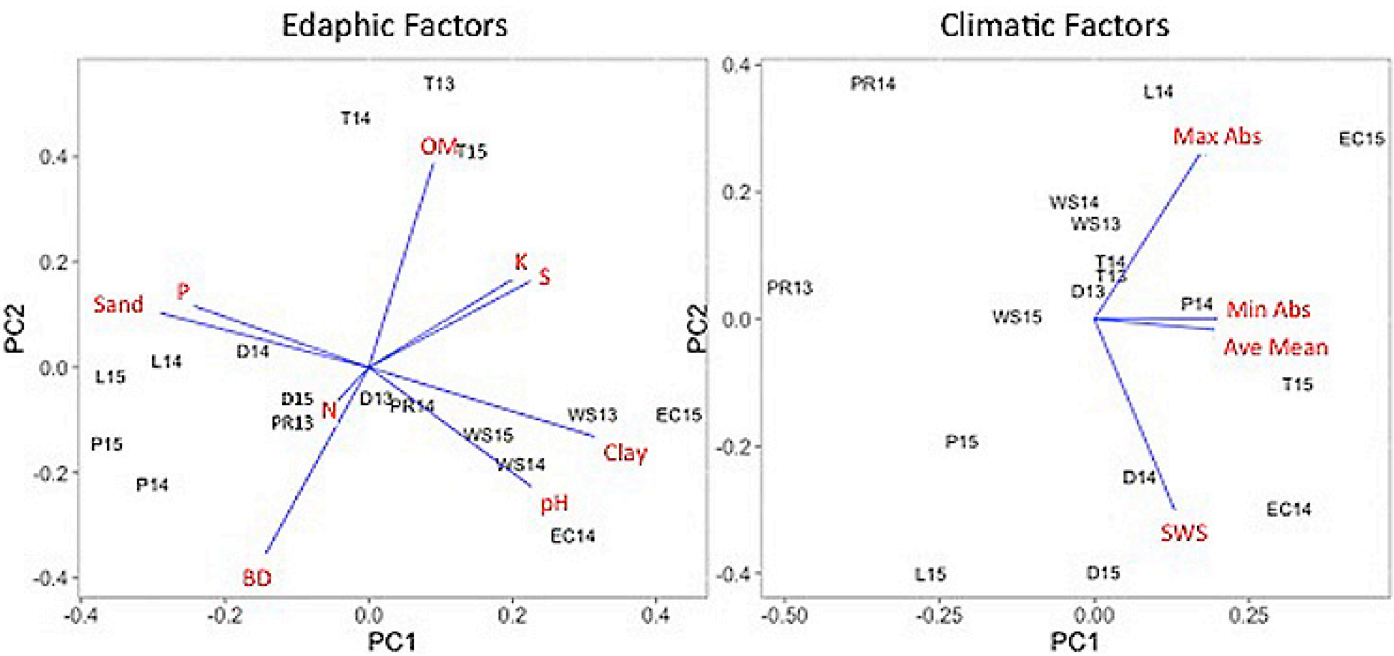

Fig. 8. Results of principle components analyses of edaphic, and climatic and water variables for the individual environments (environment code as per Table 9). BD – soil bulk density, N – nitrogen content of soil, P – phosphorus content of soil, K – potassium content of soil, S – sulfur content of soil, Sand – percent sand content of soil, Clay – percent clay content of soil, OM – organic matter content of soil, pH – soil pH. Max Abs – absolute maximum temperature of location, Min Abs – absolute minimum temperature of location, Ave Mean – average mean temperature of location, SWS – Seasonal water supply (precipitation, irrigation and starting soil water).

Table 8. Genetic correlations between environments for FA1 from the mixed model for canola. Environment code as per Table 7.

Seed yield	D13	D14	D15	E14	E15	P14	T13	T14	T15	WS13	WS14	WS15
D13	1.00											
D14	0.67	1.00										
D15	0.68	0.92	1.00									
E14	0.48	0.65	0.66	1.00								
E15	0.70	0.95	0.96	0.68	1.00							
P14	0.57	0.77	0.78	0.55	0.81	1.00						
T13	0.62	0.83	0.84	0.60	0.87	0.71	1.00					
T14	0.60	0.80	0.82	0.58	0.85	0.68	0.74	1.00				
T15	0.70	0.95	0.96	0.68	1.00	0.81	0.87	0.85	1.00			
WS13	0.63	0.85	0.86	0.61	0.89	0.72	0.78	0.75	0.89	1.00		
WS14	0.43	0.58	0.59	0.42	0.61	0.49	0.53	0.52	0.61	0.54	1.00	
WS15	0.36	0.48	0.49	0.35	0.51	0.41	0.45	0.43	0.51	0.45	0.31	1.00
Seed oil	**D13**	**D14**	**D15**	**E14**	**E15**	**P14**	**T13**	**T14**	**T15**	**WS13**	**WS14**	**WS15**
D13	1.00											
D14	0.78	1.00										
D15	0.76	0.93	1.00									
E14	0.80	0.98	0.95	1.00								
E15	0.72	0.88	0.85	0.90	1.00							
P14	0.64	0.79	0.76	0.81	0.73	1.00						
T13	0.73	0.90	0.87	0.92	0.83	0.74	1.00					
T14	0.66	0.81	0.78	0.83	0.74	0.67	0.76	1.00				
T15	0.80	0.98	0.95	1.00	0.90	0.81	0.92	0.83	1.00			
WS13	0.78	0.95	0.92	0.98	0.88	0.79	0.90	0.81	0.98	1.00		
WS14	0.80	0.98	0.95	1.00	0.90	0.81	0.92	0.83	1.00	0.98	1.00	
WS15	0.44	0.53	0.52	0.55	0.49	0.44	0.50	0.45	0.55	0.53	0.55	1.00

Table 9. Genetic correlations between environments for FA1 from the mixed model for camelina. Environment code as per Table 7.

Seed yield	D13	D14	D15	E14	E15	L14	L15	P14	P15	PR13	PR14	T13	T14	T15	WS13	WS14	WS15
D13	1.00																
D14	0.25	1.00															
D15	0.79	0.20	1.00														
E14	0.89	0.22	0.71	1.00													
E15	0.44	0.11	0.35	0.39	1.00												
L14	0.81	0.20	0.64	0.73	0.35	1.00											
L15	0.43	0.11	0.34	0.38	0.19	0.35	1.00										
P14	0.89	0.22	0.71	0.80	0.39	0.72	0.38	1.00									
P15	0.83	0.20	0.66	0.74	0.36	0.67	0.35	0.74	1.00								
PR13	1.00	0.25	0.79	0.89	0.44	0.81	0.43	0.89	0.83	1.00							
PR14	−0.16	−0.04	−0.12	−0.14	−0.07	−0.13	−0.07	−0.14	−0.13	−0.16	1.00						
T13	−0.76	−0.19	−0.61	−0.68	−0.33	−0.62	−0.33	−0.68	−0.63	−0.76	0.12	1.00					
T14	0.48	0.12	0.38	0.43	0.21	0.39	0.21	0.43	0.40	0.48	−0.07	−0.37	1.00				
T15	0.33	0.08	0.26	0.29	0.14	0.27	0.14	0.29	0.27	0.33	−0.05	−0.25	0.16	1.00			
WS13	0.09	0.02	0.07	0.08	0.04	0.07	0.04	0.08	0.07	0.09	−0.01	−0.07	0.04	0.03	1.00		
WS14	0.35	0.09	0.28	0.31	0.15	0.28	0.15	0.31	0.29	0.35	−0.05	−0.27	0.17	0.11	0.03	1.00	
WS15	0.94	0.23	0.75	0.84	0.41	0.77	0.40	0.84	0.78	0.94	−0.15	−0.72	0.45	0.31	0.08	0.33	1.00
Seed oil	**D13**	**D14**	**D15**	**E14**	**E15**	**L14**	**L15**	**P14**	**P15**	**PR13**	**PR14**	**T13**	**T14**	**T15**	**WS13**	**WS14**	**WS15**
D13	1.00																
D14	0.34	1.00															
D15	0.34	1.00	1.00														
E14	0.32	0.96	0.96	1.00													
E15	0.23	0.70	0.70	0.67	1.00												
L14	0.25	0.75	0.75	0.71	0.52	1.00											
L15	0.11	0.33	0.33	0.31	0.23	0.24	1.00										
P14	0.29	0.85	0.85	0.81	0.59	0.63	0.28	1.00									
P15	0.25	0.76	0.76	0.72	0.53	0.56	0.25	0.64	1.00								
PR13	0.34	1.00	1.00	0.96	0.70	0.75	0.33	0.85	0.76	1.00							
PR14	−0.06	−0.17	−0.17	−0.16	−0.12	−0.13	−0.05	−0.14	−0.13	−0.17	1.00						
T13	−0.31	−0.94	−0.94	−0.90	−0.65	−0.70	−0.31	−0.79	−0.71	−0.94	0.16	1.00					
T14	0.12	0.34	0.34	0.33	0.24	0.26	0.11	0.29	0.26	0.34	−0.06	−0.32	1.00				
T15	0.14	0.42	0.42	0.40	0.29	0.31	0.14	0.36	0.32	0.42	−0.07	−0.39	0.14	1.00			
WS13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00		
WS14	0.09	0.26	0.26	0.25	0.18	0.20	0.09	0.22	0.20	0.26	−0.04	−0.25	0.09	0.11	0.00	1.00	
WS15	0.34	1.00	1.00	0.96	0.70	0.75	0.33	0.85	0.76	1.00	−0.17	−0.94	0.34	0.42	0.00	0.26	1.00

shorter-season spring-type varieties, with suitable agronomic management, canola could become an economically viable cool-season crop across much of the state where wheat or other small grains are grown. Camelina yields were lower and more variable than canola, and are not economically competitive with wheat or canola. It did not offer a shorter maturation time than canola, although it did display greater cold and drought tolerance, so the possibility of camelina being viable for particular niches in Californian cropping systems needs to be investigated further.

On-going research and development for canola in California is needed to support industry development. Variety evaluation should continue and expand to examine more short-season spring types. Given the lack of significant genotype × environment effects, ongoing variety screening, at least in the short-term, can probably be at a more restricted range of locations to save resources, but should still provide data that is meaningful on a statewide basis. Agronomic questions important to the adoption of canola in the region at the present time include crop water use and appropriate irrigation management, and the effect of planting date on yield, especially as it relates to soil water and temperature.

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