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Research Paper

Measurement and simulation of water-use by canola and camelina under cool-season conditions in California

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ABSTRACT

The agricultural sector of California is one of the most diverse and economically valuable in the world, but is dominated by woody perennial, and annual warm-season crops, dependent on irrigation. These face potential problems from restrictions to irrigation water supply and climate change. Canola and camelina could be used to diversify cool-season cropping in the state, but the water use of these species in the region is poorly understood. In this study, both the total and temporal water use of canola and camelina under cool-season production conditions in California were investigated using field-based and computer modeling approaches. Total and temporal water-use of both species were found to be similar to what has been observed in other regions under cool-season conditions. Observed seasonal water uptake patterns also closely matched predictions by the Agricultural Production Systems Simulator (APSIM) model. These results inform the utilization of these species as new crops in California and also contribute to estimates of water use by these globally significant oilseeds under Mediterranean to arid climate conditions.

1. Introduction

California's agricultural sector is one of the most diverse and economically valuable in the world, but is dominated by woody perennial and annual warm-season crops that require irrigation (FAOSTAT, 2015; Tolomeo et al., 2012; USDA NASS, 2017). Alternatives to irrigation-dependent warm-season annual crops are needed due to increases in competing demands for water, together with projected increased variability and reduction in water supply under many climate change scenarios (Cayan et al., 2008; Cook et al., 2015; Jackson et al., 2012; Lee and Six, 2010; Mann and Gleick, 2015). For example, in California's Central Valley, "business as usual" scenarios forecast 26–32% increases in irrigation water demand by 2099 (Mehta et al., 2013). Globally, difficulties in forecasting regional rainfall and evaporation trends under climate change scenarios make predictions of future water constraints uncertain, but the emerging consensus anticipates worsening water scarcity in regions that already experience dry conditions, an area covering approximately 40% of the global land surface (Gosling and Arnell, 2016; IPCC, 2014; Schewe et al., 2014; Wiltshire et al., 2013).

One strategy to help farming in California adapt to a more water-limited future is through increased use of annual cool-season crops. These are produced during the period of minimum evaporative demand (fall to early spring), and can utilize winter precipitation in the region's Mediterranean to semi-arid climate for some, if not all, of their water requirements. Currently, the most extensively planted cool-season crops in California are cereals (Tolomeo et al., 2012). To facilitate adoption by growers, new cool-season crops should therefore complement or readily integrate with existing cereal production systems. Canola (*Brassica napus*) has been used to diversify cereal-based agricultural systems in multiple regions worldwide, notably Canada, Australia, Europe and the United States (Booth and Gunstone, 2004; Duff et al., 2006; Pouzet, 1994; USDA NASS, 2017), suggesting it could be used as a cool-season crop option in California. Relative to other winter oilseeds, canola generally has the highest yield potential under favorable conditions, but it can become unreliable when crop available water limits yield (Farré et al., 2007; NCDC, 2015), conditions that may prevail in some places and years of California. The oilseed species camelina (*Camelina sativa*) has lower yield potential than canola but is regarded by some as more reliable than canola under low input conditions, and has a larger temperature range for crop establish-

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ment (Allen et al., 2014; Berti et al., 2016; George et al., 2017b; Jiang, 2013; Putnam et al., 1993), and could therefore provide another winter annual alternative. There is little commercial production of either canola or camelina in California at present, although current studies suggest that both species have potential as crops in the region (George et al., 2017a; Winans et al., 2016).

The water use of both canola and camelina has been investigated, but not under Californian agro-environmental conditions (Faraji et al., 2009; Hergert et al., 2011; Hocking et al., 1997; Hu et al., 2015; Hunsaker et al., 2013; Lenssen et al., 2012; Robertson and Kirkegaard, 2005; Zeleke et al., 2014). If canola and camelina are to be considered as cool-season crops for adapting California agriculture to lower or more variable winter rainfall, or to reduced irrigation water availability, it will be necessary to develop a quantitative understanding of the water use of both species.

A broader understanding of the water used of canola and camelina can also assist in predicting potential yield responses and economic viability of these crops under differing scenarios of climatic variability (Müller and Robertson, 2014), as well as the potential risks and benefits of introducing crops into existing rotations (for example: Nielsen et al. (2005)). Thus, while the work here is motivated by the potential to diversify Californian winter production systems, the findings have broader applicability, especially given the importance of canola as the third-largest vegetable-oil source worldwide (ERS, 2012).

The computer crop model APSIM has been used to identify crop strategies for optimizing the water use efficiency of both cereals and canola production in Australia (Farré et al., 2002; Hochman et al., 2009; Robertson and Kirkegaard, 2005). APSIM is a modeling framework that combines biophysical and management modules to simulate cropping systems; it is used globally as a tool for both research and farm management (Holzworth et al., 2014; Keating et al., 2003). The APSIM-canola module is used to simulate canola production in Australia, under both current and future climates (Farré et al., 2007; Farré et al., 2002; Holzworth et al., 2014; Kirkegaard et al., 2016; Kirkegaard et al., 2003; Luo et al., 2010; McCormick et al., 2015; Robertson et al., 1999; Robertson and Kirkegaard, 2005), and George and Kaffka (2017) recently demonstrated that the model can reliably simulate the phenology, biomass accumulation, and seed yields of canola production in California under a diverse range of edaphic, climatic, and management conditions. APSIM could therefore be a valuable tool for understanding and investigating the water use of canola in California, and it would be worthwhile to test the accuracy of the model under Californias conditions. The APSIM model is unable to simulate camelina at the present time.

Here we report on work that estimated the water use of canola and camelina in California using multiple approaches. The objectives of this work were: To estimate the water use of canola and camelina under field conditions in relation to seed yield (e.g. as measured by water use efficiency, defined as the mass of seed production per unit area per mm water transpired); to make initial estimates of crop coefficients (K_c), that can then inform irrigation management; to estimate the seasonal patterns of water use of canola and camelina, and the spatial pattern of water use of both species throughout the soil profile; and to use Californian field data to test the ability of the APSIM crop model to simulate the water use of canola.

2. Materials and methods

2.1. Site details and seasonal weather information

This work utilized data from existing, multi-environment yield trials of both canola and camelina that were conducted in Califor-

Table 1
Details regarding the research sites used in this study.

Site Name	Lat	Long	Mean Winter Rainfall (mm)	Soil type	Season	Irrigation Camelina (mm)	Irrigation Canola (mm)	Precipitation (mm)	Bulk Density (g/cm3)	Permanent Wilting Point (v/v)	Field Capacity Point (v/v)	Estimated soil water content in root zone (mm)	Sand (%)	Silt (%)	Clay (%)	OM (%)	Nitrogen NO3 (ppm)	Phosphorus Bray (ppm)	Phosphorus Olsen (ppm)	Potassium (ppm)	Sulfur SO4 (ppm)
Davis	38.5	−121.8	469	Clay loam/silty clay loam	2012–13	0	0	294	1.4	11	25	253	39	29	33	2	2	6	7	144	7
					2013–14	355	355	219	1.5	10	21	319	46	29	25	2	14	15	7	149	6
					2014–15	101	101	361	1.6	10	20	441	50	27	24	2	6	7	8	153	9
El Centro	32.8	−115.4	82	Clay	2013–14	640	690	18	1.4	18	33	451	7	35	59	2	33	2	11	3	132
					2014–15	290	370	42	1.4	16	32	482	9	34	56	1	8	7	16	297	332
Lockeford	38.2	−121.7	313	Loam	2013–14	10	10	248	1.6	7	21	466	44	39	18	2	12	36	15	74	7
					2014–15	30	30	180	1.6	7	13	193	63	24	14	1	5	54	31	87	13
Parlier	36.6	−119.5	283	Loamy sand/sandy loam	2013–14	205	205	125	1.7	3	14	241	57	33	11	1	34	17	5	2	15
					2014–15	130	130	149	1.7	2	8	200	69	21	10	1	25	21	18	46	9
Paso Robles	35.6	−120.7	361	Clay loam	2012–13	0	0	182	1.2	23	45	134	34	29	37	3	73	26	13	2	8
					2013–14	0	0	155	1.1	18	36	97	29	35	36	3	11	7	6	2	8
Tulelake	42.0	−121.5	288	Sandy loam/clay loam	2013	260	260	44	0.7	26	61	55	41	36	24	4	7	19	19	240	275
					2014	280	350	50	0.7	26	61	52	52	29	20	5	22	20	31	207	39
					2015	280	350	50	0.7	34	72	54	36	31	34	4	16	20	21	162	174
West Side	36.3	−120.1	221	Clay	2012–13	40	40	99	1.3	18	37	49	13	35	52	2	15	6	5	315	58
					2013–14	135	135	75	1.4	15	31	364	22	35	43	2	12	7	4	222	41
					2014–15	180	180	141	1.3	13	27	338	29	31	41	2	5	8	8	179	53

Davis – UC Davis Campus Research Station, El Centro – UC ANR Desert Research and Extension Center, Lockeford – USDA Lockeford Plant Material Center, Parlier – UC ANR Kearney Agricultural Research and Extension Center, Paso Robles – Private farm, Tulelake – UC ANR Intermountain Research and Extension Center, and West Side – UC ANR West Side Research and Extension Center.

nia between 2012 and 2015 (Table 1) (George et al., 2017a). Seven trial sites were located to span the range of cool-season cereal cropping in California, and which represent all potential oilseed growing regions. All sites receive almost all effective rainfall during the winter season. Mean seasonal rainfall volumes ranged from 80 mm in the desert-climate of El Centro in Southern California to 470 mm at Davis in Northern California. Soil types at research sites were clays or loam variants. Notably, the El Centro site was situated on an arid paleolake with heavy clay soils and the Tulelake site was on a recently drained lakebed, with soils containing large amounts of dolomite, smectitic clays, and (relatively) high in organic matter.

At all locations, soil fertility was non-limiting for seed yield (George et al., 2017a), suggesting the importance of variable water availability for production. Specific information regarding the multi-environment trial sites and experimental methodology is provided by George et al. (2017a). All sites were managed using agronomic methods comparable to those used for commercial cereal production in the same locations. Production at all locations relied primarily on rainfall to meet crop water needs. Irrigation, if available, was used only if crops exhibited obvious water-stress, such as leaf wilting, to prevent stand failure. Irrigation was delivered via sprinklers early in the season and then via either furrow or flood later in the season.

At sowing, soil samples were taken from at least three locations in each field at depths of 0–50, 50–100, 100–150 and 150–200 cm using a soil auger. Soil samples were used for the determination of soil volumetric water content and dry bulk density. Using soil volumetric water content and bulk density values, the plant-available volumetric water content in the total soil profile (to depth of 200 cm) was estimated. The reported maximum rooting depth of the species is approximately 200 cm (Johnston et al., 2002), and field observations made in soil profiles during this research observed negligible rooting below 150 cm for either species. Chemical and physical analyses of soil samples to determine permanent wilting point and field capacity, soil textural composition, and nutrient concentrations were performed by A&L Western Laboratories (1331 Woodland Ave. Suite 1 Modesto, CA 95351), as reported in Table 1. Weather data for the sites were obtained from the California Irrigation Management Information System (CIMIS, 2015), the National Climatic Data Center (NCDC, 2015), and from in-field weather stations located at the research sites.

2.2. Volumetric soil water content monitoring and estimation of evapo-transpiration (ET_c)

At a subset of the research sites (Davis, Lockeford and West Side) the volumetric soil water content of the fields was measured using time domain reflectrometry (TDR) sensors (10HS Soil Moisture Smart Sensors and Hobo U30 data loggers; Onset Computer Corporation, 470 MacArthur Blvd. Bourne, MA 02532). The sites were chosen because they had differing soil types (Davis: silty clay loam/clay loam; Lockeford: loam;, Westside: clay), that are nonetheless suitable for using TDRs for monitoring water content, and because they are located in the Central Valley, which is the largest contiguous cereal-cropping zone of the state. The TDR sensors were approximately 20 cm long and installed vertically in the bottom of auger holes at approximately 10 cm, 50 cm, 100 cm and 180 cm below the soil surface. Each TDR sensor was installed in an individually augured hole spaced approximately 50 cm from neighboring measurement points, and in the middle of the individual crop plots. The depths were selected in order to span the reported maximum rooting depth of the species (200 cm, Johnston et al. (2002)), while having a higher density of measurements near the soil surface where soil water content was anticipated to be most variable. Two plots per species and field site were used. One measured canola plot was planted to the variety HyClass 955, a short-season spring type variety known to have high yield potential in California, and a second was another short season spring-type variety that varied by locations and year (George et al., 2017a). For camelina, one plot was planted to the variety SO-50, a variety known to have superior performance in California, and the other was a variety selected at random from the larger set of entries in the experimental layout (George et al., 2017a). Volumetric soil water content was logged by the TDR sensors between planting and harvest on a 15 min basis.

Wateruptake over time was estimated by depth-interpolating the soil water content to a depth of 200 cm, and then computing the rate of change of water content per depth on a daily timescale. Increases in soil water content resulted from measured rainfall and irrigation, and soil water depletion was attributed to evapotranspiration and deep drainage, according to the mass balance:

$$z_i \frac{d\theta_i}{dt} = P + I - ET_i - Q_{i,} \quad i = 1$$
$$= Q_{i-1} - ET_i - Q_{i,} \quad i > 1 \qquad (1)$$

Here z_i is the depth of soil layer i (as observed at the TDR); Q_i is the downward flow of water from layer i, θ is the volumetric water content, P the precipitation amount, I the water application from irrigation, and ET_i the rate of evaporation and transpiration from soil layer i. Total evapotranspiration is estimated by summing the estimate of ET_i for each soil layer. Water movement was assumed to be one dimensional (i.e. negligible lateral flow, a reasonable assumption given that all site slopes were <2%, with deep soil profiles and deep water tables, and thus no conditions to support a lateral water potential gradient). The bottom profile boundary was assumed to drain freely (a reasonable assumption for the deep, well-drained soils with unstructured soil profiles and water tables at least 10 m or greater at each site, characteristic of the floodplain-derived soils of California's Central Valley (NRCS, 2015)).

Two methods of estimating ET_i were compared, which were expected to bound the "true" values of water uptake. In the first approach, all soil water depletion in the rooted profile was attributed to plant water uptake. This approach likely over-estimates true plant water use, both because losses of water occurring due to any deep drainage are assigned to evapotranspiration, and because all direct evaporation from the soil surface and plant canopy, as well as transpiration losses, were attributed to plant uptake. In the second approach, soil water depletion that occurred within two days of an irrigation or rainfall event was excluded from the estimation of plant water uptake. This avoided attributing water losses from deep-drainage and evaporation after rainfall to plant water use. This approach likely under-estimates evapotranspiration. Since rainfall and irrigation events were infrequent (for example, there were only ten rainfall events that delivered more than 10 mm in a single day at Davis, the wettest location in both seasons), the overall error introduced by this method was likely to be small because evaporation during the winter growing season in the region is relatively low (CIMIS, 2015). Comparison of these two methods produced estimates that differed by only 25 mm/year (data not presented), therefore only the uncorrected data was used. Using these methods and assumptions, total water content, and the daily change in water content ascribed to plant uptake were plotted in depth-time plots, visualizing changes in the soil and in the plant water use profiles.

The mass balance approach used to estimate crop water use is subject to limitations and assumptions. As discussed, the water dynamics are assumed to be one-dimensional (i.e. no lateral flow). The bottom boundary of the rooted profile is assumed to approximate a free drainage boundary (a reasonable assumption since the depth to the water table, based on information provided by individual research stations, is on the order of 10 m or greater at each

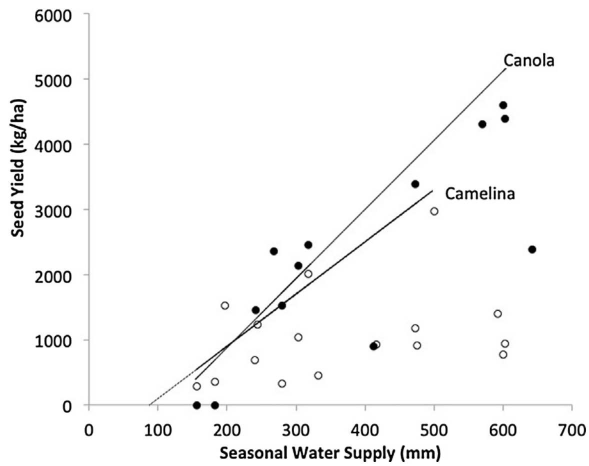

Fig. 1. The relationship between total seed yield and seasonal plant available water for canola and camelina. The linear trend line for canola was generated using the equation describing the relationship ($y = 10.6x - 1243$) previously developed by Robertson and Kirkegaard (2005). The linear trend line describing the approximate upper boundary of the camelina data was visually fitted and is described by the equation $y = 8x - 700$.

site). Deep percolation (other than in the period immediately after rain/irrigation) appeared to be minimal since only small changes in soil volumetric water content were recorded by the deepest TDRs. Implicitly, we assume that the TDR sensors reliably capture the structure and dynamics of the subsurface water distribution. The good agreement between plots supports this assumption (see Results). Nonetheless, it is possible that preferential flow could cause infiltrating water to bypass individual sensors – or conversely to be concentrated in the vicinity of the sensors. Furthermore, TDR sensors are not expected to fully capture transpiration of water from near surface sources, or evaporation from the soil surface or from water intercepted by the crop canopy, and may therefore underestimate the evaporation portion of evapotranspiration.

Crop water use efficiency was estimated by plotting crop water uptake against seed yield for the sample plots. Linear trend lines defining the upper boundary of the data were visually fitted to both species by linear regression amongst a subset of points that appeared to form an upper bound to the data (see Fig. 1). This would represent the crop response to seasonal conditions when water is used the most efficiently due to its timing in relation to crop demand with minimal unproductive losses (Robertson and Kirkegaard, 2005).

2.3. Estimation of crop coefficients (K_c)

Single crop coefficients (K_c) for both canola and camelina were calculated using daily estimates of crop evapotranspiration (ET_c) and reference evapotranspiration (ET_o) from the closest CIMIS station using a weekly moving average and then aggregated to monthly timescales (Allen et al., 1998; Zeleke and Wade, 2012). The use of an averaging window reduces fluctuations induced by variable crop and reference evapotranspiration rates which otherwise propagate into large daily variations in the crop coefficient. The crop phenological stages for canola used to interpret the monthly crop coefficients were based on visual field observations combined with simulations by the APSIM crop model; the phenological stages of camelina were based on field observations (APSIM, 2015; George and Kaffka, 2017)).

2.4. Seasonal water supply relative to yield

The seasonal water supply was estimated for all sites based on the method of Robertson and Kirkegaard (2005):

$$W = P + I + S \quad (2)$$

Where: W is the plant available water; P is the precipitation throughout the growing season; I total irrigation provided to the site; S is the estimated starting soil water content in the soil profile to a depth of 200 cm above the permanent wilting point for the soil (considered to be the volumetric water content of the soil at matric potential of −1.5 MPa). The seasonal water supply for the sites was compared to the highest yielding varieties for the site as reported by George et al. (2017a) to establish a relationship between water supply and seed yield.

An upper boundary, describing the maximum seasonal water use efficiency of canola, (described by the equation: *seed yield* = $10.6x - 1243$; $x = H_2O$ in mm, Robertson and Kirkegaard (2005)), was compared with the seasonal water use efficiency estimated here. The relationship between seasonal water supply and seed yield for camelina describing the approximate upper boundary of the camelina data was visually fitted in using the method described above.

2.5. Crop simulation modeling

The Agricultural Production Systems Simulator (APSIM v 7.4) was parameterized using data from the from the Davis, Lockeford and West Side locations as reported in George and Kaffka (2017) for each location. APSIM is a modular biophysical simulation model suitable for evaluating economic and environmental outcomes associated with crop production. APSIM contains separate simulation modules addressing plant, soil and crop management, which can be specified for different climate, soil, crop and variety conditions. Once suitably parameterized and validated for given crop/soil/climate combinations, it can be used as a decision-support for growers, as well as a regional or production-system level research tool. APSIM is extensively documented online at http://www.apsim.info/Documentation.aspx. Most relevant to this study is the SOILWAT module in APSIM, which controls soil water redistribution and usage. SOILWAT discretizes a soil column into a series of layers (Eitzinger et al., 2004). Water content in each layer is bounded by a "lower limit" (corresponding to wilting point) and saturation. During a rainfall event, surface runoff is computed using the Soil Conservation Service Curve Number method (Mishra and Singh, 2013). The remaining rainfall volume infiltrates into the upper soil layer, and the water content in this layer is updated. If the resulting water content is less than the "upper limit" (equivalent to field capacity), no further water distribution occurs. If the updated water content exceeds the upper limit, the remaining water drains to the next soil layer at a specified rate (approximated by the saturated hydraulic conductivity). Unsaturated water redistribution also occurs when soil water content lies between the lower and upper limits, and is specified by the soil water diffusivity. Water is removed from the surface soil layer by bare-soil evaporation, which occurs following a well-known two-stage model (Ritchie, 1972), and by plant water uptake. Plant water uptake is determined by a plant-specific factor and the difference between the volumetric soil water content in a given layer and a crop-specific minimum volumetric soil water content for water uptake.

The climate module of APSIM was initialized using inputs of maximum and minimum temperatures, solar radiation and rainfall obtained from the California Irrigation Management Information System (CIMIS, 2015) from weather stations at each site. Generic soil types from the APSIM database corresponding to conditions at each site were used and modified according to measured values for

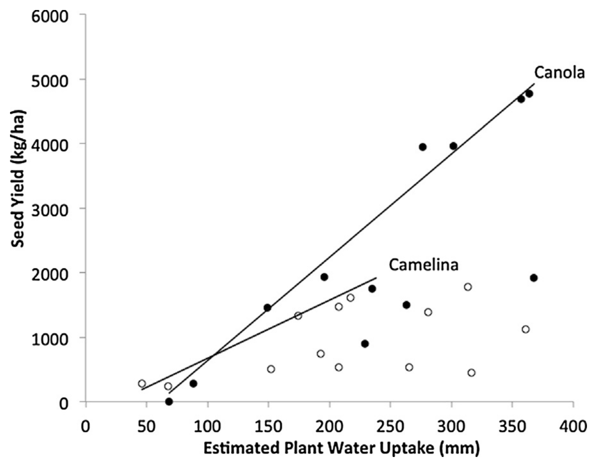

Fig. 2. The relationship between total seed yield and estimated crop water uptake for canola and camelina. The trend lines form an upper boundary for crop water use efficiency. The upper bound trend lines were visually fitted. For canola the upper boundary is described by the equation $y = 16x - 960$, and for camelina by the equation $y = 9x - 225$.

soil bulk density, starting volumetric water content, measured permanent wilting point (volumetric water content of the soil at matric potential of −1.5 MPa), drained upper limit (volumetric water content of the soil at matric potential of −0.3 MPa), nitrogen (nitrate) content, and percent organic matter from field sites (Table 1). The management module of APSIM was initialized using the agronomic management of canola crops at the individual research sites (George et al., 2017a). The cumulative crop water uptake at the sites predicted by APSIM was compared with the water uptake estimate generated use the TDR data.

3. Results and discussion

3.1. Water uptake of canola and camelina in relation to yield

A range of crop yields were observed during the study; individual plot yields varied from stand failure to 2000 kg/ha for camelina and from 900 to 4800 kg/ha for canola, and span the range of yields that can be commonly expected for camelina and canola in California (George et al., 2017a; George and Kaffka, 2017). The yield variation between sites is attributed to the amount and timing of both rainfall and periods of low or high temperature (George et al., 2017a). For example, unusually cold and dry conditions during the 2013–14 season resulted in very poor stand establishment and survival for both species at the West Side location, and late season heat stress is believed to have depressed yields in El Centro, a desert location (George et al., 2017a).

The seed yield of canola showed a positive relationship with both seasonal water supply and total water uptake, whereas camelina showed a more weakly positive relationship (Figs. 1 and 2). The relationship between yield and seasonal water use for canola proposed by Robertson and Kirkegaard (2005) for an equiseasonal rainfall environment, with a seasonal water use efficiency of approximately 11 kg/ha/mm, above 120 mm to a limit of 450 mm, is similar to the upper boundary of the data for canola in Fig. 1. Based on the figures, the seasonal water supply that maximized canola seed yields was approximately 500–600 mm. The threshold yield for canola to be economically competitive with wheat in California is approximately 3000 kg/ha (Winans et al., 2016), which would require a seasonal water availability of approximately 400 mm. If supplemental irrigation is needed due to dry periods, or dry years, or if the species are produced in the low-rainfall southern Central Valley, our findings suggest the irrigation needs of canola will be very similar to other cool-season crops grown in the region such as wheat (DWR, 2015; Jackson et al., 2006). The upper boundary visually fitted to the camelina data suggests a seasonal water use efficiency of approximately 8 kg/ha/mm above 90 mm, with a maximum yield of 3000 kg/ha for a seasonal water supply of 500 mm. The mean maximum yields observed in California to date are more typically 1000–2000 kg/ha for camelina (George et al., 2017a; Kaffka et al., 2015), and predicted water requirements corresponding to commonly observed yields are 250–300 mm. A seasonal water supply from all sources of approximately 300 mm is available in most years throughout extensive areas of the state, therefore total plant available water may not be an important determinant of yield for camelina in California. The trend lines for the two species intersect at an estimated seasonal water availability of 225 mm (Fig. 1).

The maximum estimated water uptake based on TDR measurements was approximately 360 mm for canola and 200 mm for camelina (Fig. 2), which is lower than for the seasonal water supply. Evaporative losses from sprinkler and flood irrigation can amount to 25–50% of total seasonal water supply (Connellan, 2013). The lower estimates of estimated water uptake relative to seasonal water supply here are therefore reasonable given the TDR does not account for evaporative losses from the soil surface or crop canopy. The maximum water uptake efficiency is estimated to be approximately 16 g/mm/ha for canola, closer to the observed maximum in Australia (Robertson and Kirkegaard, 2005), and 9 g/mm/ha for camelina, with the trend lines intersecting at approximately 100 mm (Fig. 2).

The poorer relationship between seasonal water supply and yield for camelina, and large numbers of data points falling below the upper boundary, suggest environmental factors apart from water supply strongly influence yield. The population of camelina varieties evaluated in the multi-environment trial displayed cryptic genotype-by-environment effects, yield variation could therefore not be attributed to any single environmental factor (George et al., 2017a). Seed yield being weakly related to seasonal evapotranspiration in camelina has been observed by other workers (French et al., 2009; Hunsaker et al., 2011; Hunsaker et al., 2013).

Additional work will be required on water use by canola and camelina in California's diverse production environments, but the results reported here are in general agreement with those reported for both species when grown as a cool-season crop in other regions (Amjad, 2010; CCC, 2015; Hergert et al., 2011; Hu et al., 2015; Hunsaker et al., 2013; Lenssen et al., 2012; McCaffery, 2006; Zeleke et al., 2014). The close relationship between the findings of Robertson and Kirkegaard (2005) and Zeleke et al. (2014), and the results observed here, suggests previously established relationships between seed yield and water use developed for spring-type canola in Australia are broadly applicable to spring-type canola production in California.

Camelina has a lower yield potential than canola, but is regarded by some as more reliable under water-limited conditions (Allen et al., 2014; Francis and Campbell, 2003; George et al., 2017a; Gunasekera et al., 2009; Hunt and Norton, 2011; Jiang, 2013; Putnam et al., 1993). A number of authors have investigated the potential of camelina to produce seed at lower seasonal moisture levels than canola as well as other crops with similar planting periods (Chen et al., 2015; Hulbert et al., 2012). Camelina seed can germinate successfully at matric potentials of −1.5 MPa, while canola germinates poorly at these potentials (Jiang, 2013). At the Paso Robles location in both seasons canola failed due to insufficient seasonal water, but camelina yielded approximately 300 kg/ha (George et al., 2017a). Our results suggest camelina has a water use efficiency lower than canola, but a lower minimum water requirement for germination and seed production. We therefore propose that camelina will produce a seed crop, and has the potential to

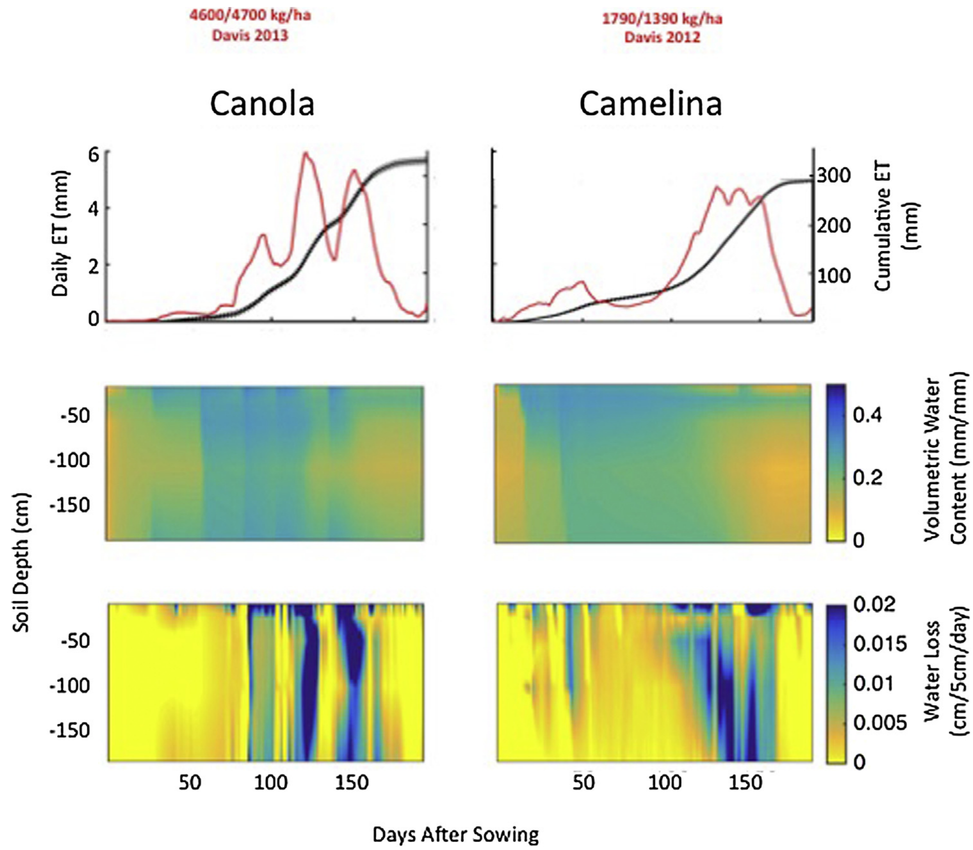

Fig. 3. Representative temporal water use patterns of canola and camelina as measured by TDR. The canola was grown at Davis in 2013, seed yields were 4600 and 4700 kg/ha for the two varieties. The camelina was grown at Davis in 2012, seed yields were 1800 and 1400 kg/ha. Top Figure: Cumulative evapotranspiration (black line) and daily evapotranspiration (red line). Middle figure: soil volumetric water content over time. Bottom figure: The depth of water lost throughout time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

out-yield canola, only at a seasonal water availability of less than approximately 200 mm.

3.2. Temporal and spatial water use of canola and camelina, and estimates of single crop coefficients

Temporal and spatial patterns of water use varied between locations and years. Examples of spatial and temporal water use in the soil profile estimated using TDR data are presented in Fig. 3. The figures are representative of a high-yielding crop of both species and therefore show clear temporal water use patterns.

Trends in daily evapo-transpiration were broadly similar to what has been reported by other workers for both species in other regions (Hergert et al., 2011; Hunsaker et al., 2013). The water use of both species was similar, and relatively low, for the first three months after planting (November, December, and January), and peaked during the following two months (February and March). This corresponds with the phenological stages of germination and rosette formation (0–80 days after sowing), stem elongation, flowering, and seed set (80–110 days after sowing; and seed maturation: >110 days after sowing) for spring canola grown as a winter crop in California (George et al., 2017a). This pattern of water use also corresponds with the phenology of camelina observed in California (George et al., 2017a).

Over the first 50–100 days after planting, changes in the soil volumetric water content were relatively small and generally occurred at depths of 50 cm or less. Following that period, there was a rapid change in soil volumetric water content deeper in the soil profile, indicating that both species had begun to draw on water at those depths. This coincides with the period of increased daily evapo-transpiration in both species starting in early spring. Changes in soil volumetric water content were usually greatest at soil depths of less than 100 cm, however changes at depths of over 150 cm also were observed. End-of-season soil trenches were excavated to remove the TDRs, and roots of both crops were observed at depths of at least 150 cm, although root density was low compared with shallower soil layers. This suggests both species have the ability to access soil water at or below 150 cm but will preferentially utilize shallower water if it is available. Sites with poor growth showed lesswater use from deep in the soil profile (data not shown).

There was a variation in estimated crop coefficients within and between sites. This is to be expected given that growing conditions were sometimes suboptimal and crops were not fully irrigated (Allen et al., 1998). When averaged across sites on a monthly basis, the single crop coefficient estimates are similar to or slightly lower than those reported elsewhere for canola and camelina (Allen et al., 1998; Hunsaker et al., 2013) (Fig. 4). Camelina had marginally higher crop coefficients than canola earlier in the season, which we believe corresponds to the species tolerance of lower temperatures and more rapid early growth, but lower values during peak water use relative to canola, which corresponds with the species smaller over-all leaf area and total biomass production. More controlled conditions, and quantitative observations of crop phenology, will be needed to more exactly determine the timing of the initial-, mid- and end-season crop coefficients (Allen et al., 1998).

3.3. Simulation of water use using the APSIM crop model

This study found there was general agreement between the APSIM predictions of crop water uptake and TDR estimates of crop

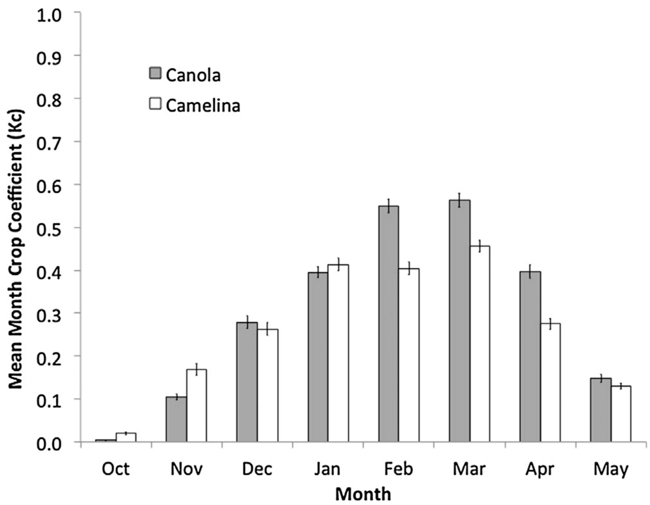

Fig. 4. Mean daily crop coefficient (Kc) estimates for canola and camelina grown as cool-season crops at three locations in California. Error bars show standard error of prediction.

water uptake by canola in terms of both seasonal patterns and total water uptake (Fig. 5). This test of the model was limited in scope, and additional field studies will be required to confirm the accuracy of APSIM in the region, but the results suggest the model is able to estimate both temporal and total water uptake patterns of canola under cool-season production conditions in California with a reasonable degree of accuracy.

These findings, along with those of George and Kaffka (2017), suggest APSIM could be used within California for the following: 1) Understand the potential water requirements of canola relative to cereals in the cool-season cropping systems of the state; 2) Reduce risk in water-limited canola production systems by yield- forecasting given initial soil water conditions and seasonal water inputs; 3) Identify management strategies for maximizing the water use efficiency of canola, and; 4) Explore the viability of canola as a crop in the region under current and future rainfall and irrigation supply scenarios.

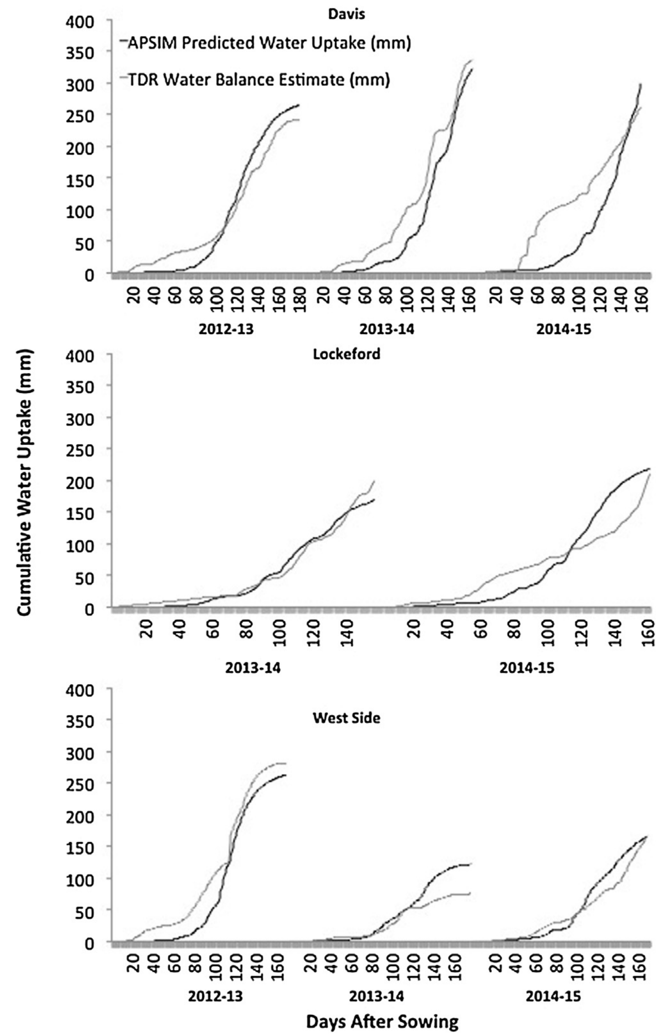

Fig. 5. The cumulative crop water uptake at the sites predicted by APSIM compared with the water uptake estimate based on the volumetric soil water data measured by TDR sensors.

4. Conclusions

This study explored the water use of canola and camelina as cool season crops in California. Using ideal agronomic management practices, the seasonal water availability required to achieve economically viable yields of canola in California will be approximately 400 mm. Camelina may be a more reliable alternative to canola when the total seasonal water supply is less than 250 mm, but lower seed yields and oil content may limit its adoption. The mean winter precipitation throughout much of the northern Central Valley and near coastal dry farming regions of California should therefore be sufficient to achieve high yield potentials for both species without irrigation. Irrigation requirements for canola will likely be similar to or lower than wheat in the same areas. Observed total and temporal water use for both canola and camelina are comparable to what has been observed for the species in other regions under cool-season conditions, notably Australia, and from field trial and crop modeling data from California (George et al., 2017a; George and Kaffka, 2017). Research and agronomic management practices, regarding water use developed in Australia therefore have relevance for California.

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