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Canola as a New Crop for California: A Simulation Study

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ABSTRACT

The agricultural sector of California is one of the most economically valuable and diverse in the world, but is dominated by perennial tree, vine and forage crops, as well as warm-season annual species that are dependent on irrigation. The diversity of less water-intensive annual cool-season crops is limited and wheat (*Triticum aestivum* L.) is the primary crop. Canola (*Brassica napus* L.) could diversify annual cool-season cropping in the state. Our study used field data from a multi-environment canola variety trial to test the ability of the Agricultural Production Systems Simulator (APSIM) model to simulate canola production in California. APSIM was able to accurately simulate canola yields in diverse regions, and consequently was used to investigate the yield potential of canola in California, using different irrigation management strategies, under both current and anticipated future climate scenarios. These simulations predict that canola should have high mean yields throughout California, given suitable management and variety selection. The long-term mean yield for short-season, spring-type, canola in the central valley of California is predicted to be more than 4800 kg/ha with supplemental irrigation. Under rain-fed conditions in the northern central valley mean yields are predicted to be 3500 kg/ha. This should make canola economically competitive with cool-season cereals. Without additional improvements in variety adaptation or management changes, our simulations suggest the yield of canola in California will decline modestly, but remain economically viable, under future climate scenarios.

Core Ideas

- The accuracy of the Agricultural Production Systems Simulator crop model for simulating canola production in California was tested.
- The crop model accurately predicted canola yields across the state.
- Simulations support observations from multi-environments trials that canola has both high mean yields and yield potential in California.
- The simulation results suggest canola is a viable alternative crop for diversifying cool-season annual cropping in California.
- Canola could maintain economically viable yields under climate change scenarios projected for the region.

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Canola is an important oilseed crop globally, with well-established industries in several countries (FAOSTAT, 2015). Canola oil is commonly used for both human consumption (Duff et al., 2006; Johnson and Fritsche, 2012), and biodiesel production, and canola seed meal is used as feed for several livestock species (Duff et al., 2006; Newkirk, 2009). Current demand for these products in the United States exceeds domestic production (USDA NASS, 2015). Canola is commonly used to diversify and improve both yield and profitability in cereal-based agricultural systems (Booth and Gunstone, 2004; Duff et al., 2006; Pouzet, 1994). It can have synergistic effects on the productivity of subsequent cereal crops, by acting as a disease break, suppressing weed growth, and by providing more flexibility in chemical weed control options (Angus et al., 2015).

The agricultural sector of California is one of the most economically valuable and diverse in the world, but it is dominated by perennial tree, vine, and forage crops, as well as warm-season annual species, that are dependent on irrigation (FAOSTAT, 2015; Tolomeo et al., 2012; USDA NASS, 2015). Cool-season annual crop alternatives are limited, and dominated in land area by wheat, with little to no commercial canola production in the state at the present time (Tolomeo et al., 2012; USDA NASS, 2015).

The climate of California is predicted to become warmer, drier, and more variable (Cayan et al., 2008; Parry et al., 2007; Pierce et al., 2013), leading to both increased irrigation demand for existing crops and reduced irrigation water availability (Jackson et al., 2012; Lee and Six, 2010). One proposed strategy to adapt agriculture to anticipated irrigation constraints involves the increased use of crops with lower water demand (Moser et al., 2012). By diversifying cool-season cropping, canola has the potential to aid the adaptation of the state's agricultural sector to more water-limited conditions.

In California, there is a long-standing interest in canola as a cool-season crop (Cohen and Knowles, 1983; Knowles, 1980; Knowles et al., 1981). It has been evaluated intermittently since the late 1970s, and this work suggests it has high yield potential in the region (Cohen and Knowles, 1983; Kaffka et al., 2015; Knowles, 1980; Knowles et al., 1981). A recent multi-environment trial conducted under primarily rain-fed conditions found mean yields in the state could exceed 3000 kg/ha, with varieties at some locations exceeding 5000 kg/ha, potentially making the crop economically competitive with cereals (George et al., 2017a, Winans et al., 2016).

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Abbreviations: APSIM, Agricultural Production Systems Simulator.

New crops can be valuable to farming industries, but widespread adoption of new crops faces a number of barriers. These include both a lack of reliable information regarding yield potential in the proposed production environment, making it difficult to assess the economic value of the crop, and a lack of knowledge regarding appropriate agronomic management, making crop production risky (Janick, 1996; Janick and Whipkey, 2002; Janick and Whipkey, 2007). There are likely to be insufficient resources to conduct the field-based research and development activities needed to adequately address these barriers. A crop simulation model, if reliable, is therefore a valuable tool for assessing the yield potential of a new crop and for exploring agronomic management strategies to optimize production. A crop model can also refine research questions and guide further research and development activities. Crop models also provide an avenue to explore the impact of potential future climate changes on crop production (White et al., 2011).

APSIM is a modeling framework combining biophysical and management modules that simulate cropping systems (Holzworth et al., 2014; Keating et al., 2003). The APSIM-canola module has been used to accurately simulate canola production in Australia, under both current and future climates (Farré et al., 2002, 2007; Holzworth et al., 2014; Kirkegaard et al., 2003; 2016; Luo et al., 2010; McCormick et al., 2015; Robertson et al., 1999; Robertson and Kirkegaard, 2005). Similarly, APSIM may facilitate canola research and development in California. There is no published literature regarding the testing of APSIM for any aspect of canola production in the United States and the accuracy of the model under Californian conditions is unknown.

Crop production in California encompasses a range of climates, soil types, and latitudes. Large areas of the state are similar to other Mediterranean climates around the world (Grigg, 2002), in particular to southwestern Australia, a region which currently supports an extensive canola industry and in which the APSIM-canola module has been widely tested and used (ABARES, 2015; Robertson and Lilley, 2016). California also includes high-altitude, cool continental climates, and lowland deserts, where irrigation is required to meet nearly all crop water needs (Peel et al., 2007). Evaluation of APSIM for the simulation of canola production in California therefore provides a useful evaluation of the model in an agro-ecologically diverse and internationally important agricultural region.

This work had two objectives: first, to use field data from a multi-environment trial of canola conducted in California to test the ability of the current version of the APSIM-canola module to simulate canola yields throughout the state, and; second, if the model can accurately simulates field data, to use it to investigate the yield of canola in California under different irrigation management strategies across the cereal cropping regions of the state, using current and anticipated future climate scenarios.

MATERIAL AND METHODS

Testing of the APSIM Crop Model for Canola in California

Data from a multi–environment trial of canola, conducted over a 3-yr period across California (George et al., 2017a), were compared to simulations by the APSIM (APSIM v 7.4) for the same locations (Table 1). The multi-environment trial focused on short-season spring-type canola varieties, including varieties developed for Australia. Parameters for the specific canola varieties evaluated in the multi-environment trial were not available in the current APSIM-Canola module. Field data were therefore compared to simulations using the generic, early-, mid-, and late-season canola varieties already parameterized in the model. Canola displays relatively little genotype × environment interaction in California (George et al., 2017a). In these trials, the top 10 highest yielding varieties were all short-season spring types. Yields among these varieties did not differ significantly from each other across environments, therefore for each field trial location the mean yield across the best 10 varieties were compared to the seed yields predicted by APSIM.

Data for growing season phenology and biomass accumulation of canola were collected at the Davis location in the second season of the multi-environment trial. The climate of the site is broadly representative of cereal-cropping regions of the northern California central valley, and the canola producing regions of southwestern Australia. The short-season spring canola variety HyClass 955 (Winfield Solutions, P.O. Box 64101, Saint Paul, MN, 55164–0101) was sown on 15 Nov. 2013 using methods described by George et al. (2017a). Seven biomass harvest dates were applied factorially to separate plots arranged as a randomized completed block with three replicates. Biomass was harvested from a 1.5 by 6.4 m area by cutting plants approximately 10 cm above the ground. A subsample of approximately 1 kg was taken and dried at 40°C for 1 wk for the determination of moisture content. At each biomass harvest, observations of the phenological stage were taken, and a random sample of five plants were taken from each plot to determine biomass partitioning among leaves, stems, flowers and buds, and pods and seeds. The data from this field study were compared to simulations using the generic, early-, mid-, and late-season, canola varieties available in the APSIM-canola module database.

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) and The National Climatic Data Center (NCDC, 2015) (Table 1). Generic soils from the APSIM database were used and modified according to measured values for soil bulk density, starting soil moisture content, measured wilting point 1500 kPa (15 bar), drained upper limit 33 kPa (1/3 bar), N (nitrate) and organic matter from the multi-environment trials locations were used (George et al., 2017a). The management module of APSIM was initialized using the agronomic management of canola crops at the individual trial sites. Details regarding other parameter values used for the modeling are provided in the supplemental material. Some soil water parameters (such as Cona, U, KL, and XF (APSIM, 2012)) were unknown for the study sites. A formal sensitivity analysis to test the effect of varying these soil water parameters was not conducted but the values vary minimally among clay and loam soil types in the APSIM model database, and informal tests found that changing the values in line with variation observed in the model database affected yield predictions by only a few percent. See supplemental material for the values used.

Simulation of Canola Production under Different Irrigation Management Scenarios in California

Locations within the cereal-cropping regions of California with suitable weather data were selected for the simulations (Table 1, Fig. 1). The locations represent the possible canola production regions of California and are broadly representative of the climatic and edaphic conditions within these regions. Locations were subdivided into agro-ecological and agro-economic zones used previously to analyze new crop adoption in the region by Kaffka and Jenner (2011). For each location, simulations were conducted for the full duration of the climate record available for the site (1982–2013).

The known soil types from 4000 ha of land around the chosen sites were obtained and used to develop a soil representative of the area (NRCS, 2015). The majority of soils in the areas of interest were found to have relatively undifferentiated profiles over the maximum rooting depth of canola (approximately 200–250 cm). For the purpose of the simulations, soils were therefore treated as having functionally undifferentiated profiles to a depth of 250 cm for all soil properties except wilting point, drained upper limit, N, and organic matter. For these parameters, the top 50 cm of the soil profiles were divided into 10-cm increments. Summary details regarding soil properties are provided in the supplemental material.

The ideal fall sowing window for canola in all parts of California, except the high elevation (1240 m) inter-mountain region, is between October and November. This is comparable to the early fall sowing season for cereal crops in the state (Jackson et al., 2006), and early November had been identified as the ideal sowing time for oilseeds in California by Knowles et al. (1981). This is consistent with the seasonally equivalent recommended sowing date for canola in climatically comparable regions of southern Australia (Kirkegaard et al., 2016). A preliminary analysis using the methods of Lilley et al. (2015) found that through most of California sowing in the last 2 wk of October should minimize frost risk at flowering and heat stress during seed fill for shorter-season varieties. When sowing prior to the middle of October, under rain-fed conditions, it is likely that there will be insufficient soil moisture to support germination in much of the region. After approximately the last week of November low soil temperatures may cause germination and establishment problems in central and northern California (George et al., 2017b; Nykiforuk and Johnson-Flanagan, 1994; Nykiforuk and Johnson-Flanagan, 1999). For these reasons, 15 October was set as the earliest sowing date and 20 November as the latest sowing date. Under a rain-fed scenario it was assumed growers would sow at the onset of winter rains. The sowing trigger for rain-fed canola was a volumetric soil water content of 0.05 mm/mm, above the crop lower limit, in the top 10 cm of the soil profile.

Table 1. Locations in California used for testing the accuracy of the APSIM model for simulating canola production in California, and locations used for simulating canola production across the state.

Region	Site name	Seasons of data available 1982–2013	Irrigation	Latitude	Longitude	Mean growing season rainfall (Oct.–June)	Common soils	Multi-environment trial (harvest year)
						mm		
Sacramento Valley	Colusa	31	Rain-fed/Furrow	39.2	−122.0	336	loams, clay loams	2013/2014/2015
Sac. Valley	Davis	32	Rain-fed/Furrow	38.5	−121.8	469	silty clay loams, clays	
	Durham	32	Rain-fed/Furrow	39.6	−121.8	408	clay, fine loam	
	Stockton	27	Rain-fed/Furrow	38.0	−121.3	416	clay loams, silty clay loams	
	Brentwood	29	Rain-fed/Furrow	37.9	−121.7	350	clay, clay loam	
Northern San Joaquin Valley	Parlier	31	Furrow	36.6	−119.5	283	loamy sandy, fine sandy loam	2014
NSanJ. Valley	West Side	32	Furrow	36.3	−120.1	221	clay, clay loam	
	Los Banos	26	Furrow	37.1	−120.8	151	clay loam	
Southern San Joaquin Valley	Kettleman	32	Furrow	36.0	−119.9	104	clay	2013/2014/2015
SSanJ. Valley	Shafter	31	Furrow	35.5	−119.3	119	sandy loam	
Imperial Valley	El Centro	23	Furrow	32.8	−115.4	82	clay, silty clay loam	2014/2015
Imp. Valley								
Central coast	Paso Robles	32	Rain-fed/Fallow	35.6	−120.7	361	fine loams, sandy loams, often shallow	2014
	Atascadero	10	Rain-fed/Fallow	35.5	−120.7	258	fine loams, sandy loams, often shallow	
Inter-mountain	Tulelake	25	Furrow	42.0	−121.5	288 (May-Sept.)	silty clay loam	2013/2014/2015

This is in line with the soil water content shown to achieve reliable germination of canola in loam soils (Blackshaw, 1991; Williams and Shaykewich, 1971).

The Inter-Mountain region of California, represented by Tulelake, is an important spring cereal-growing region and experiences a mild-summer continental climate (Peel et al., 2007). The area supports cereal cropping on both lacustrine soils derived from former lakebeds and on mineral soils. Both soil-types were simulated. Like cereals in that region, canola is best suited to spring planting. The optimal sowing time for canola was assumed to be as close to the last killing frost date for the region, which is approximately 8 May based on inspection of climate records. This was the earliest sowing date used in the simulation.

In the simulations, organic matter, soil water and N were reset at the start of each season (1 October), to treat each season independently. Soil water was reset to 25% of maximum plant available soil water, consistent with the mean starting water content observed for soils across California in the multi-environment field trial (George et al., 2017b).

The generic, mid-season, spring-type canola variety in the release version of APSIM-Canola was used for all simulations relating to scenario tests (see Results for justification). The sowing depth was set to 2 cm, at 100 plants/m^2 with a row spacing of 15 cm, comparable to the values from the multi-environment trial (George et al., 2017a). A starting value of 20 kg/ha in the top 50 cm of the soil profile was used for residual soil nitrate, consistent with field observations (George et al., 2017a). For simulation purposes, pre-plant N fertilization was 400 kg N/ha, in the form of urea. Preliminary analyses suggested this ensured N was non-limiting for yield even under very high yield-potential scenarios. Surface irrigation with a minimum water delivery of 100 mm per irrigation was assumed since it is the most common irrigation method currently utilized by wheat growers in the region.

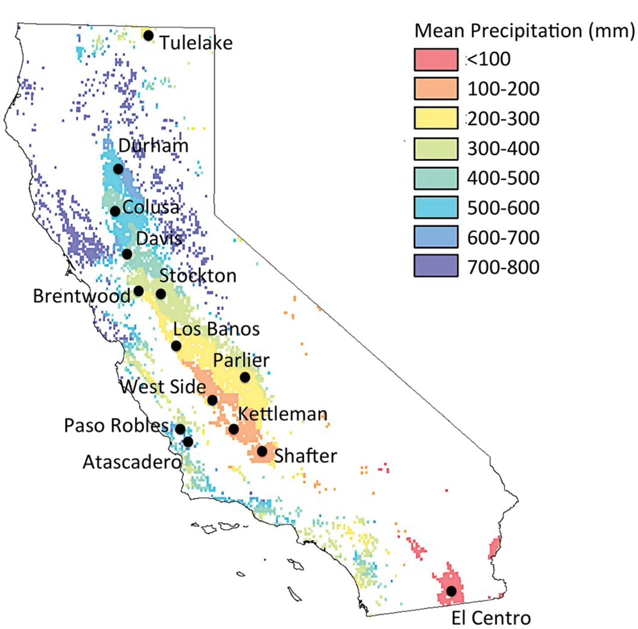

Fig. 1. Locations chosen for APSIM simulation of canola production in California. Colored areas show major cereal-growing regions of the states and annual rainfall (George et al., 2017a).

The following irrigation management strategies were simulated (terms in parentheses refer to the code used for these treatments in subsequent figures and tables):

1. Rain-fed farming with no irrigation, with a soil moisture sowing constraint (Rain-fed).
2. A 100 mm pre-sowing irrigation, to facilitate establishment, and then no further irrigation (Pre100mm).
3. A pre-sowing irrigation to completely saturate the soil profile to 250 cm. Total irrigation amount and plant available water was dependent on soil type (Fullprof).
4. A pre-sowing irrigation of 250 mm, and a second irrigation at flowering of 250 mm, regardless of soil water holding capacity, to simulate growers providing 500 mm of water, which is the approximate maximum evapo-transpirational demand of canola expected under California conditions, applied at easily-observable phenological stages (Split).
5. Applications of 100 mm of irrigation when the soil water deficit in the top 200 cm of the soil profile reached 100 mm. Representing irrigation throughout the growing season assuming the use of volumetric soil water content monitoring equipment (Furrow).
6. Simulation run continuously without annual resetting of soil water content, with sowing between 15 October and 1 December if available soil water in the profile had accumulated to either 50, 100, or 150 mm. This represents a typical rain-fed cereal production system of the central coast region where cropping and fallow alternate approximately yearly depending on soil water availability (Fallow).

Extreme temperatures (<0°C and >30°C) during flowering and grain-fill can cause yield suppression in canola, but these are currently not simulated by APSIM (Lilley et al., 2015). The number of extreme temperature days during the simulated flowering and grain-fill period were therefore quantified. The number of days with minimum temperatures lower than 0°C, and maximum temperatures greater than 30°C, during this period were calculated as the proportion of the total number of days during that time interval. This is similar to the approach

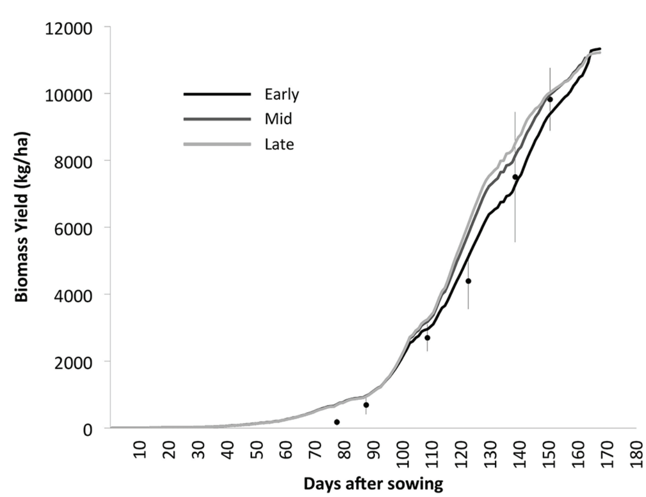

Fig. 2. The relationship between observed field data and APSIM model output for seasonal biomass accumulation. Lines– APSIM predictions for different canola maturity classes. Points– field observations. Error bars show standard deviation of field-based measurements of the 10 highest yielding cultivars at each location.

developed by Lilley et al. (2015) to explore these risks for canola across a range of production environments and management strategies.

Simulation of Climate Change Scenarios

Climate change scenarios were simulated using the APSIM climate control module. Canola production was simulated under current climatic conditions, based on historic CIMIS records, and atmospheric CO_2 levels, as well as under climatic conditions and atmospheric CO_2 levels predicted for 2065 (Cayan et al., 2008) (Table 2).

Statistical Analyses

The root mean squared error (RMSE), and the linear regression coefficient between simulated and observed data (R^2), were used to evaluate the accuracy of the APSIM predictions of seed yield relative to field data from the multi-environment trial. Flowering time of the field studies was qualitatively assessed on a weekly basis (George et al., 2017a). The correlation of the field observations of flowering with the APSIM prediction of flowering time is presented to provide an additional test of the model. The RMSE is not provided given low precision of the flowering data.

Supplemental statistical analyses were conducted using the Agricolae CRAN package R (Mendiburu, 2015) in the program R (R Development Core Team, 2012). Tests for significance between different management scenarios, within regions, were conducted using ANOVA. Assumptions of an ANOVA were tested by visual inspection of plots of variance heterogeneity and normality of residuals. Data for extreme temperature days (<0°C and >30°C) were zero-inflated, so tests for significance between treatments were conducted using a non-parametric Kruskal–Wallis rank sum test in R. As a measure of risk, and to assess the likelihood of achieving particular seed yields, a cumulative frequency analysis was conducted to visually compare management strategies.

RESULTS

Model Evaluation

There was good agreement between observed and predicted values for biomass accumulation (Fig. 2) and phenology (Table 3) at the Davis location in the second season. Early biomass accumulation was overpredicted for all maturity classes, possibly reflecting that biomass was cut 10 cm above the ground rather than at ground level, and therefore measured aboveground biomass yield was underestimated. The mid- and late-maturity classes generated more comparable biomass accumulation patterns than the early maturity class, and the final biomass yield predicted by the mid- and late-maturity classes more closely matched field data. The timing of phenological events predicted for the mid- and late-season maturity classes more closely matched field observation than for the early-season variety.

Predicted days to flowering (APSIM stage 6.0-start of flowering) ($R^2 = 0.9$) were correlated with field observations from the multi-environment trials, despite field observation being qualitatively rated (Fig. 3). Seed yield across all sites was predicted by the APSIM model with good accuracy by all maturity classes: early ($R^2 = 0.92$, RMSE = 450, $y = 0.88x$); mid- ($R^2 = 0.92$, RMSE = 392, $y = 0.92x$); and late ($R^2 = 0.88$, RMSE = 520, $y = 1.01x$). The early and mid-maturity classes generated more accurate simulations of yield data than the late-maturity class.

The mid-maturity class was selected for further simulations on the grounds that it provided the best simulation of biomass accumulation, phenology, and maximized the linear regression coefficient and minimized the root mean squared error (RMSE) for yield (Fig. 4). The one-to-one relationship shows that at low-yield sites seed yields were overestimated. The primary discrepancy between the model predictions and the field observations was at the Paso Robles site, where plants grew but failed to produce seed, while the model predicted seed yields of approximately 500 kg/ha.

Table 2. A summary of climatic changes simulated using APSIM (from Cayan et al. (2008)).

Region	Season	Unit	Low emissions scenario	High emissions scenario
Northern California	Summer	°C	1.9	2.6
	Winter	°C	2.3	1.3
	Summer	mm/%	–15.5	–16.0
	Winter	mm/%	–1.1	0.5
Southern California	Summer	°C	1.6	2.2
	Winter	°C	1.1	1.4
	Summer	mm/%	–8.5	–12.5
	Winter	mm/%	–7.5	7.5

Table 3. The timing of phenological growth stages of canola observed at Davis in the second year of the research project, compared with APSIM simulations of the same location. APSIM growth stages: Sowing 0.0 to 1.9, germination 2.0 to 2.9, emergence 3.0 to 3.9, vegetative 4.0 to 4.9, floral initiation 5.0 to 5.9, flowering 6.0 to 6.9, and seed fill 7.0 to 7.9. Value for Buds, Flowers, and Pods indicates the proportion of plants in the sample.

Harvest	Dates	Plant phenological stage based on observations from field study	Stage predicted by APSIM					
			Early	Mid-	Late	Early	Mid-	Late
Harvest 1	30 Jan.	Vegetative	floral_initiation	end_of_juvenile	end_of_juvenile	5.4	5.0	4.8
Harvest 2	12 Feb.	Floral initiation	floral_initiation	floral_initiation	floral_initiation	5.8	5.4	5.1
Harvest 3	4 Mar.	Flowering	start_grain_fill	flowering	flowering	7.0	6.6	6.3
Harvest 3	18 Mar.	Flowering/Early grain fill	start_grain_fill	start_grain_fill	start_grain_fill	7.3	7.2	7.1
Harvest 5	31 Mar.	Later flowering/Grain fill	start_grain_fill	start_grain_fill	start_grain_fill	7.6	7.5	7.3
Harvest 6	15 Apr.	Grain fill	start_grain_fill	start_grain_fill	start_grain_fill	7.8	7.7	7.5

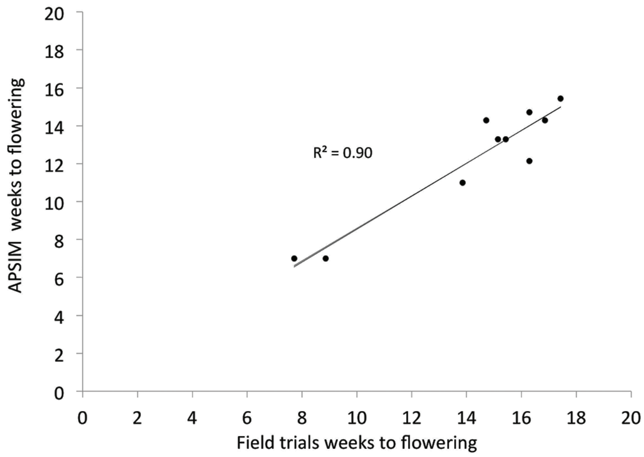

Fig. 3. The relationship between observed field data and APSIM model output for days to flowering for the multi-environment field trials.

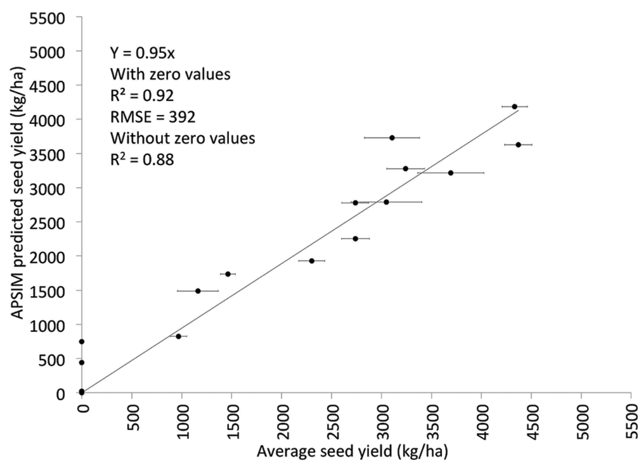

Fig. 4. The relationship between observed field data and APSIM model output of a generic mid-season variety for canola seed yields. The line shows 1:1 relationship. Error bars show standard deviation of field-based seed yield measurements.

Simulation Results: Yield Potential of Canola and the Effect of Different Irrigation Management Strategies

Yields of rain-fed canola were found to vary considerably in both spatial and temporal terms (Fig. 5). The highest-yielding region when crop production was simulated without irrigation was the Sacramento Valley, where mean yields were predicted to be 3500 kg/ha, followed by the central coast with 2500 kg/ha. The standard deviation of yield for the central coast was approximately twice that of the Sacramento Valley, indicating greater inter-annual variation. Under the rain-fed scenario, yield and annual rainfall for individual years were positively correlated, with maximum yields obtained in seasons with approximately 500 mm of cumulative precipitation, and a lack of response to larger amounts (Fig. 6). For the same rain-fed sites, estimated crop water uptake was closely correlated with yield (Fig. 7). Maximum predicted crop water uptake for rain-fed canola was approximately 400 mm. Under rain-fed conditions, fall-planted and spring-planted sites exhibited different predicted linear relationships between water uptake and seed yield, with fall-planted locations exhibiting a water use efficiency of approximately 13 kg/ha/mm, compared with 7 kg/ha/mm for the spring-planted sites.

In all regions where it was simulated, the use of irrigation resulted in increased yield and reduced production risk between years (Fig. 5 and 8). There were also significant differences in yield between different irrigation treatments. Simulated irrigation effects reflect differing potential grower strategies and can be summarized as follows:

- Irrigation applied to replace soil water depletion by the crop resulted in significantly higher yields than other management strategies. Applying two irrigations, at sowing and flowering, resulted in the next highest seed yields in these regions (split).
- In the Sacramento Valley, mean yields from split irrigation (500 mm) and pre-sowing irrigation to fill the soil profile (approximately 300 mm of water) did not differ significantly.

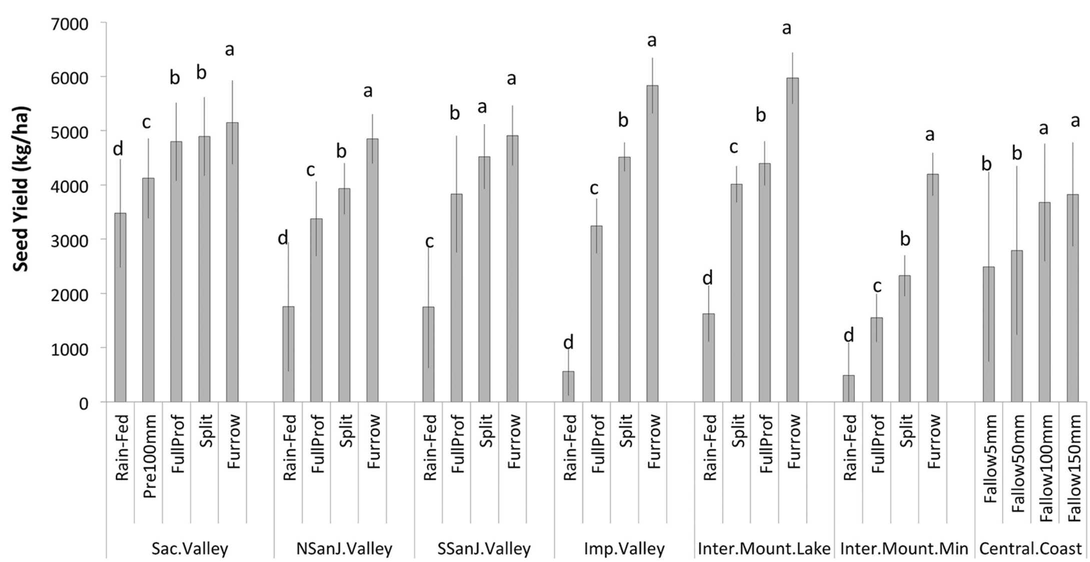

Fig. 5. Mean yields for different production strategies predicted by the APSIM model for canola in California. Rain-fed– non-irrigated, Pre100mm– pre-sowing irrigation of 100mm, FullProf.– full soil profile at sowing, Split–irrigation applied pre-sowing and at flowering, Furrow–irrigation throughout growing season to meet soil water depletion by crop (see Methods for explanation of treatments). Error bars show standard deviation of model estimates across 30 seasons. Commonality of letters indicates no significant difference within location.

- In the southern San Joaquin Valley, yields from split irrigation and irrigation to replace soil water depletion resulted in the highest yields, and did not differ significantly.

Estimated mean yields, given ideal management for each region, were:

- In the Sacramento Valley, mean seed yields of approximately 5000 kg/ha were predicted with irrigation supplied to meet soil water depletion. Approximately 550 mm of irrigation was required to match soil water depletion throughout the growing season (data not presented). Mean yields of 4800 kg/ha are predicated with split irrigation, or irrigation applied pre-sowing to fill the soil profile, regardless of seasonal rainfall.
- In the San Joaquin Valley, yields of 4900 kg/ha were predicted with irrigation supplied to meet soil water depletion. Approximately 550 mm of irrigation was required to match soil water depletion (data not presented). Mean yields of 3900 and 4500 kg/ha are predicted for the northern and southern San Joaquin Valley, respectively, if irrigation was applied only at sowing and flowering.
- In the Imperial Valley, and Inter-Mountain region on lacustrine soils, irrigation to match soil water depletion resulted in estimated seed yields of approximately 5800 and 6000 kg/ha, respectively. For the Inter-Mountain region on mineral soil, irrigation to match soil water depletion resulted in yields of 4200 kg/ha. Average cumulative seasonal irrigation amounts required to achieve these yields were predicted to be 1000 mm in the Imperial Valley, and 1500 and 770 mm for the Inter-Mountain lacustrine and mineral soils, respectively.

In the central coast region, there was a significant increase in mean seed yields, and a decrease in yield variation between years, from simulated fallowing relative to sowing every year. The differences in yields between sowing conditionally at 100 and 150 mm of soil water were not significant, due to large variation between years, although the highest mean yields achieved were approximately 3800 kg/ha from sowing with 150 mm of stored soil moisture. Under this scenario sowing occurred in 21 out of 33 yr.

Simulation Results: Climate Change Scenarios

The effect of climate change on crop yield varied between regions and irrigation scenarios (Tables 4 and 5). Predicted yields under both rain-fed and irrigated conditions in the central valley and central coast locations were reduced by the future climate scenarios under a low emissions scenario, but not always significantly. For example, in the central valley locations, yields under climate change were reduced by approximately 8% relative to current climatic conditions. Predicted yields for both rain-fed and irrigated conditions under a high emissions scenario for the central valley locations did not differ significantly from current climates. In the Inter-Mountain region, yields were predicted either not to be significantly affected by climate change or to increase.

With the exception of the Inter-Mountain region, the model did not predict significant changes in crop water uptake under either climate change scenario. Crop duration was predicted to decrease significantly due to climate change in most regions. Throughout the central valley, the days to harvest were predicted to be reduced by approximately 12 d between the current climate and the climate of the high emission scenario. The model predicts that climate change will result in canola biomass and seed yield accumulation occurring more rapidly after sowing, and maturing earlier, than under the current climate (Fig. 9 and 10).

The mean number of days per season experiencing frost (<0°C) during flowering and seed set were very low in most locations, occurring on average less than 1 d during each season, and the days during which seed yields would be sensitive to low temperature were predicted to remain unchanged or decrease slightly due to climate change (Table 5). With exception of the Inter-Mountain region, extreme heat (>30°C) during seed fill was also rare, occurring on average only 1 d in every 10 seasons, and was predicted either not to occur or increase only slightly under climate change (Table 5).

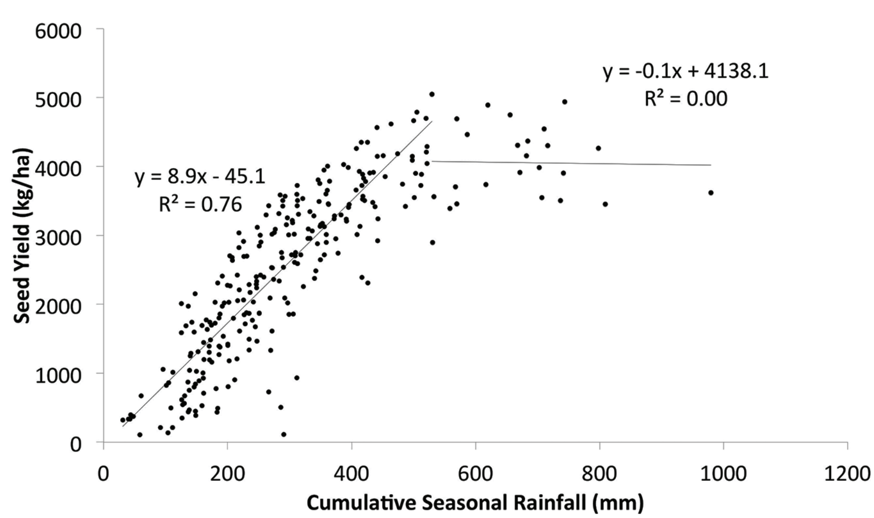

Fig. 6. The relationship between seed yield and cumulative seasonal precipitation for rain-fed canola for sites in California predicted by the APSIM model. Rainfall considered in two classes, 0 to 500 mm and 500 mm or greater per season.

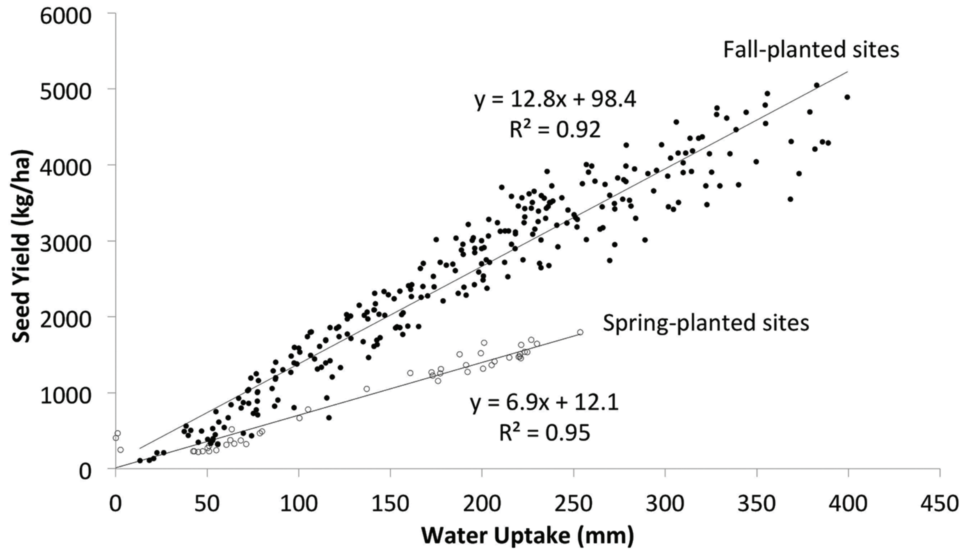

Fig. 7. The relationship between seed yield and total crop water uptake at rain-fed sites of canola in California predicted by the APSIM model.

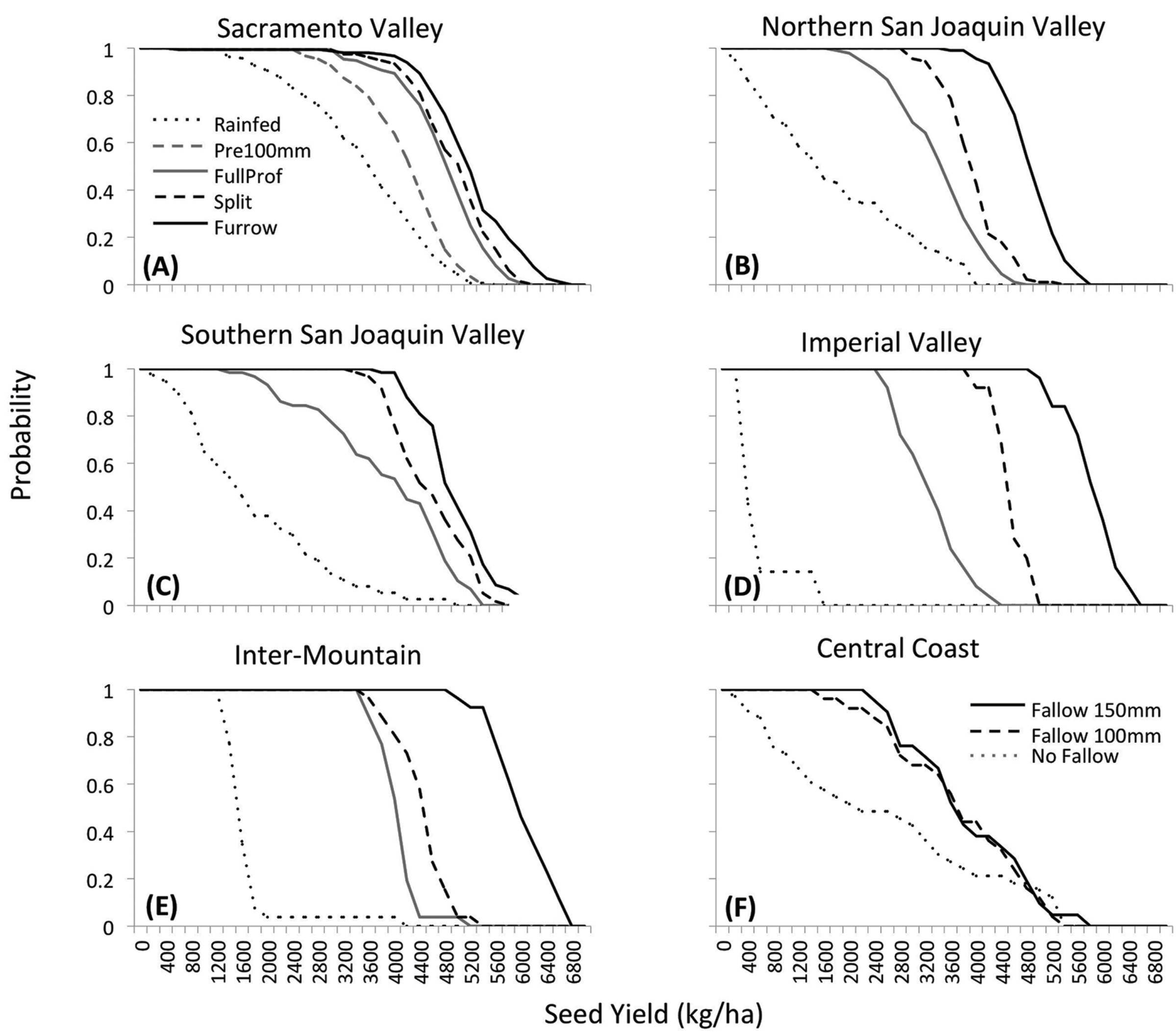

Fig. 8. Plots showing probability exceedance for seed yield of canola in regions of California for select crop management strategies (see Methods for explanation of treatments).

Table 4. The seed yield, plant water uptake, and days to harvest for canola predicted by the APSIM model under current and future climates (see Methods for explanation of climate scenarios). Current– current climate. Low–high emission scenario by year 2065, High–high emissions scenario by year 2065. Rain-fed– non-irrigated, Pre100 mm–pre-sowing irrigation of 100mm, FullProf.–full soil profile at sowing, Split–irrigation applied pre-sowing and at flowering, Furrow–irrigation throughout growing season to meet soil water depletion by crop (see Methods for explanation of treatments). Standard deviation of model estimates across years in parenthesis. Commonality of letters indicates no significant difference.

Region	Treatment	Climate	Years	Yield	Water uptake	Days to harvest
				kg/ha	mm	
Sacramento Valley	5 mm	Current	136	3560 (1050)a	270 (80)a	190 (10)a
		Low	136	3220 (850)b	250 (70)b	170 (10)c
		High	136	3470 (1000)ab	260 (80)ab	180 (10)b
	FullProf.	Current	149	4900 (750)a	400 (70)a	200 (10)a
		Low	149	4230 (680)b	350 (80)b	170 (10)c
		High	149	4800 (720)a	390 (80)a	180 (10)b
	Furrow	Current	149	5390 (800)a	470 (110)a	200 (10)a
		Low	149	4460 (780)b	380 (110)b	170 (10)c
		High	149	5230 (820)a	460 (120)a	180 (10)b
Northern San Joaquin Valley	Split	Current	89	4030 (490)a	310 (40)a	190 (10)a
		Low	89	3940 (470)a	300 (40)a	180 (10)b
		High	89	4090 (500)a	320 (40)a	180 (10)b
	Furrow	Current	89	5000 (460)a	420 (60)a	190 (10)a
		Low	89	4790 (530)a	400 (70)a	180 (10)b
		High	89	4920 (550)a	410 (70)a	180 (10)b
Southern San Joaquin Valley	Split	Current	58	4660 (630)a	380 (70)a	190 (10)a
		Low	58	4490 (560)a	370 (70)a	180 (10)b
		High	58	4670 (590)a	380 (70)a	180 (10)b
	Furrow	Current	58	5100 (580)a	440 (80)a	190 (10)a
		Low	58	4850 (590)a	420 (90)a	180 (10)b
		High	58	5040 (620)a	440 (90)a	180 (10)b
Imperial Valley	Split	Current	25	4580 (280)a	480 (20)a	160 (4)a
		Low	25	4390 (260)a	480 (20)a	160 (4)b
		High	25	4430 (300)a	490 (20)a	160 (4)b
	Furrow	Current	25	6080 (530)a	710 (90)a	160 (4)a
		Low	25	5980 (520)a	730 (90)a	160 (4)b
		High	25	6300 (540)a	770 (100)a	160 (4)b
Inter-mountain–lake bed soil	Split	Current	26	4050 (360)a	670 (220)a	130 (3)a
		Low	26	3960 (360)a	710 (250)a	130 (3)a
		High	26	3960 (370)a	730 (280)a	130 (3)a
	Furrow	Current	26	6310 (480)c	1060 (150)c	130 (3)a
		Low	26	6650 (500)b	1220 (160)b	130 (3)a
		High	26	7240 (520)a	1370 (160)a	130 (3)a
Inter-mountain–mineral soil	Split	Current	26	2360 (380)a	370 (190)a	130 (3)a
		Low	26	2360 (370)a	400 (190)a	130 (3)a
		High	26	2380 (370)a	410 (190)a	130 (3)a
	Furrow	Current	26	4200 (400)a	650 (70)a	130 (3)a
		Low	26	4200 (400)a	650 (70)a	130 (3)a
		High	26	4200 (400)a	650 (70)a	130 (3)a
Central coast	5 mm	Current	36	2750 (1660)a	230 (110)a	190 (9)a
		Low	36	2400 (1570)a	210 (110)a	180 (9)b
		High	36	2790 (1620)a	240 (120)a	180 (9)b
	Fallow	Current	25	3710 (1140)a	310 (70)a	200 (10)a
		Low	23	3650 (1070)a	310 (60)a	190 (8)b
		High	25	3810 (1140)a	340 (70)a	180 (10)b

Table 5. The number of frost and heat days during sensitive phenological periods of canola predicted by the APSIM model for current and future cliamtes. Current– current climate. Low– high emission scenario by year 2065. High–high emissions scenario by year 2065. Rainfed–non-irrigated, Pre100 mm–pre-sowing irrigation of 100 mm, FullProf.–full soil profile at sowing, Split–irrigation applied pre-sowing and at flowering, Furrow–irrigation throughout growing season to meet soil water depletion by crop (see Methods for explanation of treatments). Standard deviation of model estimates across years in parenthesis. Commonality of letters indicates no significant difference.

Region	Treatment	Climate	Frost days per season	Heat days per season
Sacramento Valley	5 mm	Current	1.2 (2.1)a	0 (0.1)a
		Low	0 (0.2)a	0 (0.1)a
		High	0.3 (1)a	0 (0)a
	FullProf.	Current	1.5 (2.5)a	0 (0.1)a
		Low	0.2 (0.5)b	0 (0.1)a
		High	0.4 (0.9)ab	0 (0.1)a
	Furrow	Current	1.5 (2.5)a	0 (0.1)a
		Low	0.2 (0.5)b	0 (0.1)a
		High	0.4 (0.9)ab	0 (0.1)a
Northern San Joaquin Valley	Split	Current	0.8 (1.2)a	0 (0.4)a
		Low	0.3 (1.1)ab	0.1 (0.4)a
		High	0.2 (0.4)b	0 (0.3)a
	Furrow	Current	0.8 (1.2)a	0 (0.4)a
		Low	0.3 (1.1)ab	0.1 (0.4)a
		High	0.2 (0.4)b	0 (0.3)a
Southern San Joaquin Valley	Split	Current	0.3 (0.7)a	0 (0)a
		Low	0.2 (0.7)a	0 (0.1)a
		High	0.1 (0.5)a	0 (0.1)a
	Furrow	Current	0.3 (0.7)a	0 (0)a
		Low	0.2 (0.7)a	0 (0.1)a
		High	0.1 (0.5)a	0 (0.1)a
Imperial Valley	Split	Current	0 (0.2)a	0 (0.2)a
		Low	0 (0.2)b	0.1 (0.4)a
		High	0 (0.2)ab	0.1 (0.4)a
	Furrow	Current	0 (0.2)a	0 (0.2)a
		Low	0 (0.2)b	0.1 (0.4)a
		High	0 (0.2)ab	0.1 (0.4)a
Inter-mountain–lake bed soil	Split	Current	0 (0)a	4.1 (3.3)a
		Low	0 (0)a	6.8 (4.1)a
		High	0 (0)a	7.8 (4.4)b
	Furrow	Current	0 (0)a	4.1 (3.3)a
		Low	0 (0)a	6.8 (4.1)a
		High	0 (0)a	7.8 (4.4)b
Inter-mountain–mineral soil	Split	Current	0 (0)a	4.1 (3.3)a
		Low	0 (0)a	6.8 (4.1)a
		High	0 (0)a	7.8 (4.4)b
	Furrow	Current	0 (0)a	4.1 (3.3)a
		Low	0 (0)a	4.1 (3.3)a
		High	0 (0)a	4.1 (3.3)a
Central coast	5 mm	Current	1 (2.2)a	0 (0)a
		Low	0.6 (1.3)a	0.1 (0.6)a
		High	0.7 (1.5)a	0.1 (0.5)a
	Fallow	Current	0.7 (1.3)a	0.1 (0.4)a
		Low	0.4 (1)a	0 (0)a
		High	1.1 (1.8)a	0 (0.2)a

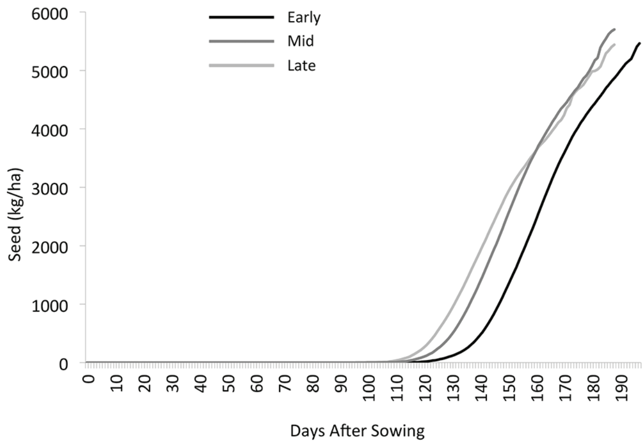

Fig. 9. Biomass accumulation for the Sacramento Valley locations under current (Current) and future (Low and High emissions) climate scenarios (see Methods for explanation of climate scenarios).

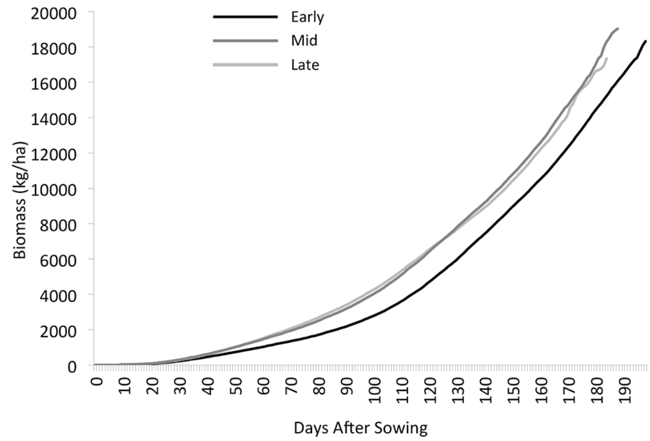

Fig. 10. Seed yield accumulation for the Sacramento Valley locations under current (Current) and future (Low and High emissions) climate scenarios (see Methods for explanation of climate scenarios).

DISCUSSION

This study found that the release version of the APSIM-canola module simulates the phenology, biomass accumulation, and seed yields of canola in California with a high degree of accuracy, comparable to Australian validations of the model (Farré et al., 2002; Kirkegaard et al., 2016; Robertson and Lilley, 2016; Robertson and Holland, 2004). Continued testing of the APSIM-canola module in California will be necessary but the results of our tests, and the thorough evaluation of the APSIM-canola module in regions of Australia that are climatically comparable to California, suggest the model can be used to simulate canola production in different regions of California with a reasonable degree of confidence.

The Yield Potential of Canola in California under Different Irrigation Management Scenarios

The APSIM model was used to investigate the yield of canola in California under different irrigation management scenarios across the diverse cereal cropping regions of the state, comparing current and anticipated future climate scenarios. These simulations, and the results of the previous statewide multi-environment trial of canola (George et al., 2017a; Kaffka et al., 2015), strongly indicate that with suitable management canola should have high mean yields in California.

Rain-fed Production Scenario

The primary limiting factor for rain-fed canola production in southern Australia, which is climatically comparable to California, is precipitation (Si and Walton, 2004; Walton et al., 1999). The APSIM model predicts similar production limitations to rain-fed canola in California. Only the northern central valley region has a high enough mean winter precipitation to support economically viable rain-fed canola production. The model predicts mean yields of rain-fed canola in the Sacramento Valley will be 3500 kg/ha, which is in good agreement with field trial data (George et al., 2017a). Rain-fed yields in other regions of the state are lower, and in many cases canola production will either be economically risky or non-viable without irrigation, similar to the situation with cool-season cereals in the region (Jackson et al., 2006; Winans et al., 2016).

The simulated yields of rain-fed canola are higher than the mean yields for canola commonly observed in other regions of North America, which are also primarily rain-fed. The long-term mean yield of canola in the United States (North Dakota, Oklahoma, Minnesota, Idaho, Montana) for all years in which data was available at the time of writing was approximately 1700 kg/ha, with no difference between predominantly warm- or cool-season production (USDA NASS, 2015). For further comparison, the mean yield of canola from the U.S. National Winter Canola Variety Trials between 2003 and 2012 was 2000 kg/ha (Assefa et al., 2014) and the mean yield for top-performing winter canola in multi-environment trials in North Carolina was 1800 kg/ha (George et al., 2012).

Irrigated Production Scenarios

In Australia, the highest-yielding canola crops (5000 kg/ha or more) are predominantly achieved with well-managed irrigation (Christy et al., 2013; Sprague et al., 2015). Given the wide availability of irrigation infrastructure in California, irrigation could be used strategically to improve yields and reduce risk in canola production. Irrigation is commonly used for cereal production in lower rainfall regions, or dry winter periods, of California and our simulations show irrigation will most likely be necessary for reliable canola production in these regions as well. The model results find that the use of irrigation to supplement winter precipitation will lead to significantly higher and more reliable yields of canola than rain-fed production, even in the northern part of the central valley where average rainfall is predicted to be adequate for economically viable production.

With optimal irrigation management, the long-term yield potential for short-season spring canola in the central valley of California is predicted to be between 4800 and 5200 kg/ha. For production situations without soil moisture monitoring capacity a split irrigation application–a pre-sowing irrigation and irrigation prior to flowering–is predicted to be a lower-yielding but simpler management strategy. Using this management method, yields of 4000 to 4900 kg/ha are predicted.

The model predicts very high yield potential (approaching 6000 kg/ha), and water use, for irrigated canola in the Imperial Valley and Inter-Mountain regions of California. Yield predictions of 6000 kg/ha are larger than the highest mean yields observed in the multi-environment trial data used to test the model predictions (George et al., 2017a), and total irrigation amounts required to achieve yields of 6000 kg/ha are predicted to be 1500 mm, which is twice average reference evapotranspiration for the same time period in the region (CIMIS, 2015). Seasonal irrigation requirements of up 1500 mm are considerably greater than known water use by existing crops in the Inter-Mountain region. The model predictions should therefore be treated cautiously until further field validation is conducted. Single plot yields close to 6000 kg/ha have been observed by our research group in California, however, and seed yields from canola of close to 8000 kg/ha are reported by other workers (Assefa et al., 2014; Christy et al., 2013; Jones, 2008), and APSIM can accurately simulate canola yields up to 7500 kg/ha (Robertson and Lilley, 2016).

The high yield predictions in Imperial Valley and Inter-Mountain region are attributed to warm winter temperatures, and excellent soils and moderate early summer temperatures, respectively. The mean daily temperature for December in the Imperial Valley location is 12°C, vs. 7°C for the Davis location, resulting in greater vegetative growth to support high seed production in the Imperial Valley. Inspection of the simulation results show the average aboveground biomass production at the end of December in Davis was 1500 kg/ha, compared with approximately 3700 kg/ha simulated at El Centro (data not presented). The exceptional lacustrine soils of the Tulelake basin have very low bulk density (<1.0) and very high water holding capacity, and are not well characterized in the APSIM model.

Fallowing Scenario

In the rain-fed farming areas of the central coast of California, growers commonly practice fallowing to increase soil water storage and increase water availability for alternate year cereal crops. The simulation suggests that in medium to low rainfall areas in this region canola production could also be more reliable if management methods that preserve and accumulate soil moisture are practiced. Potential yields of 3600 kg/ha, are predicted if canola is only sown when at least 100 mm of soil water is available in the root zone.

Viability of Canola as a Crop in California Based on the Simulation Results

The economic potential of canola production in California remains unproven given that it is not currently produced in the region, but economic analyses and field trials suggest the crop could compete economically with wheat, and displace wheat land area under favorable price relationships, if predicted yields of 3000 kg/ha or higher can be reliably achieved (George et al., 2017a; Kaffka and Jenner, 2011; Winans et al., 2016). The results of this simulation study provide additional evidence that canola could be an economically viable cool-season crop in California.

The average land area of winter wheat in California is 140,000 ha a year, although there is significant inter-annual variation (USDA NASS, 2015). Given the yields predicted here, if canola can become a component of these farming systems potential production in California is large relative to the size of the current U.S. canola industry. Our study suggests the state could contribute significantly to the expansion of the national canola industry as a whole.

Climate Change Impacts

We used APSIM to investigate the impact of climate change on canola production in California. Similar simulations have been made for other common California crops (Lee and Six, 2010). Without either improvements in variety adaptation, or management changes, the yield of canola in the central valley and central coast of California is forecast to decline modestly under potential low emissions scenarios. By 2065, mean annual yields could decline by almost 20% in some locations in the central valley. This is attributed to a predicted reduction in time to phenological maturity caused by higher temperatures, causing a reduction in total biomass accumulation at flowering. Predicted total water use in these regions tended to be unaffected by climate change, and combined with a reduction in total yield, suggests lower water use efficiency under climate change. Yields were not predicted to decline for the high emissions scenario. The stability of predicted yields under climate change in both rain-fed and fully irrigated management simulations suggests additional C fertilization in the high emissions scenario offsets the effect of increased temperatures. Interestingly, yields were predicted to increase in the Inter-mountain or Imperial Valley regions under both low and high emissions scenarios. The underlying nature and cause of this requires further investigation. Despite the declines in yield predicted for some parts of California under climate change, canola yields should remain economically viable given current economic predictions (Winans et al., 2016).

It would be informative to investigate the response of canola varieties with later maturity classes to future climates. This would require testing and parameterizing the APSIM-canola module in California for locally adapted later-maturity canola varieties. With further model development, and additional field data, APSIM could be used to identify traits to better adapt canola to climate change that could be targets for selection and breeding.

Current Limitations of the Simulations

There are potential limitations to the present simulation that could be addressed by further research:

1. The irrigation management scenarios simulated here were chosen based on methods growers in the region already use, or are likely to use, but other management options, for example, irrigation at other phenological stages, could be considered.
2. Extensive lodging and yield loss from excess soil moisture (hypoxia/anoxia) has been observed by our research group in some canola trials in California. It therefore may not be possible to irrigate crops to full yield potential under all the conditions simulated, depending on the irrigation technology available, rainfall and soil type.
3. Increased climatic variability could lead to greater mean yield reductions in canola than a simple change in mean climatic conditions over all (Luo et al., 2010). For practical reasons, only mean climatic changes were simulated here, therefore yield decline under future climates could vary from those predicted if climate variability was increased in ways that affect crop performance.

CONCLUSIONS AND FUTURE RESEARCH

This study found that the release version of the APSIM-canola module is able to reliably predict canola seed yields under cool-season production conditions in California. Scenario testing with the model suggests suitably adapted canola varieties have high yield potential in the cereal-growing regions of California. The mean yield for the crop in the northern central valley is predicted to be 3500 kg/ha under rain-fed conditions, and over 4800 kg/ha throughout the central valley with suitable irrigation management. On-going model testing is needed. To further improve the accuracy and precision of the APSIM-canola module for California data regarding the phenology, and the seasonal biomass, and yield accumulation, of locally adapted canola varieties is needed (Robertson and Lilley, 2016).

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