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Modeling

Adapting CROPGRO for Simulating Spring Canola Growth with Both RZWQM2 and DSSAT 4.0

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ABSTRACT

Currently, canola (*Brassica napus* L.) is gaining importance as a potential feedstock in biodiesel production industries, increasing the demand for canola production acreage. Agricultural system models that simulate canola growth and yield will help to assess the feasibility of canola production under various agroclimatic conditions. In this study, we adapted the CROPGRO model for simulation of spring canola in both Root Zone Water Quality Model (RZWQM2) and Decision Support System for Agrotechnology Transfer (DSSAT 4.0). Soil water, phenology, leaf area index (LAI), biomass, plant height, and grain yield data from irrigation experiments conducted in 2005 on a Weld silt loam soil (fine, smectitic, mesic Aridic Argiustoll) in the semiarid climate at Akron, CO were used for model parameterization and calibration. Similar data from 1993, 1994, and 2006 were used for validation. Species and cultivar parameters for canola were developed using data from literature or by calibrating the existing CROPGRO-faba bean (*Vicia faba* L.) parameters. Grain yields across various irrigation levels and seasons were simulated reasonably well by RZWQM2 with root mean square error (RMSE) of 215 kg ha^{-1} and index of agreement (d) of 0.98. Seasonal biomass development was simulated with RMSEs between 341 and 903 kg ha^{-1}, d between 0.55 and 0.99, and R^2 between 0.85 and 0.98. The CROPGRO-canola parameters developed were also tested within the DSSAT 4.0 cropping systems model and found to produce results with similar accuracy.

Canola is a cool-season edible oil crop that may be suitable for crop production in the central Great Plains of the United States (Nielsen, 1997) although yield reductions are seen under deficit water and high temperature conditions (Faraji et al., 2009; Young et al., 2004).

Canola is grown in both Canada and United States as an alternative crop to winter wheat as well as a spring crop incorporated into the wheat–fallow system in the Great Plains (Brandt and Zentner, 1995; Nuttal et al., 1992; Nielsen, 1997). Interest in cultivation of canola is expanding primarily due to its potential use as a renewable energy crop for production of biodiesel (Pavlista and Baltensperger, 2007) to potentially offset the shortage of the conventional nonrenewable petroleum-based fuels. While the importance of canola as a potential oil seed crop in the Great Plains of the United States has been recognized in the past couple of decades (Minor and Meinke, 1990), the basic agronomic research trials for development of location-specific agromanagement needed for successful cultivation of this crop in the area are lacking (Vigil et al., 1997).

The climate of the semiarid Great Plains of the United States is characterized by high precipitation variability and high growing season temperatures. Winter wheat-based cropping systems incorporating summer fallow under conventional tillage (WF-CT) dominated agriculture in the Great Plains during the 20th century (Peterson et al., 1993; Derksen et al., 2002; Norwood et al. 1990). The WF-CT cropping system in the semiarid Great Plains can have serious adverse impacts on the soil environment due to potential wind and water erosion and subsequent losses of soil organic matter and productivity. Spring canola could replace summer fallow in this region when favorable soil water conditions exist at planting time. However, canola has been found to be susceptible to heat and water stress and as such, it is essential that it is planted at the right time to fit into the agroclimate of the area (Brandt and McGregor, 1997; Stoker and Carter, 1984; Nielsen, 1997). In the semiarid region of Western Australia, early sowing combined with early flowering cultivars increased canola production (Si and Walton, 2004).

While the increasing use of canola for biodiesel could reduce fossil fuel use, little is known about canola yield and quality responses to climate change and increasing atmospheric CO_2 concentrations. Development of agricultural system simulation models make it possible to integrate and synthesize the quantitative understanding of the genotype and environment, and edaphic control on crop growth and development (Ahuja et al., 2000; Jones et al., 2003; McCown et al., 1996; Meyer and Curry, 1981). Additionally, development of a canola model for use within cropping systems models such as the DSSAT 4.0 and RZWQM2 will generate valuable potential production data for canola grown in rotation with wheat (*Triticum aestivum* L.) and other crops under the varying water availability and temperature conditions of the Great Plains. These simulation results will be valuable for assessing the use of canola to

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Abbreviations: DSSAT 4.0, Decision Support System for Agrotechnology Transfer; LAI, leaf area index; LSGI, line-source gradient irrigation; RMSE, root mean square error; ROS, rainout shelter; RZWQM2, Root Zone Water Quality Model; WF-CT, wheat–fallow conventional tillage.

diversify cropping systems and the viability of canola as an alternative crop for biodiesel production in the region.

Efforts in Australia to simulate canola using the APSIM model led to the development of APSIM-canola (Robertson et al., 1999b). APSIM-canola was found to be suitable for simulation and assessment of production risks associated with canola cultivation in the semiarid climate of Australia (Holland et al., 1999; Robertson et al., 1999a; Farre et al., 2002). CERES-based canola models were developed by Husson et al. (1998) and Gabrielle et al. (1998a, 1998b). Those models simulated biomass and N dynamics in response to climate, N, and water supply. Crop phenology was divided into phases, which were modeled based on daily temperature and photoperiod. Potential aboveground biomass production was predicted from LAI (and pod area index during grain filling), radiation interception by the crop, and the crop's radiation use efficiency. Kiniry et al. (1995) described the parameterization of the generic crop growth subroutine within the EPIC model for simulating canola yield in Canada. They reported simulated canola yields ranging from 84 to 125% of measured yields.

Another model that is more mechanistic than the CERES model is the CROPGRO model available in the DSSAT package (Boote et al., 1998; Jones et al., 2003) in which, the photosynthetic biochemical process equations of Farquhar et al. (1980) and Farquhar and von Caemmerer (1982) are applied in an hourly leaf-level to canopy scaling approach with hedge-row light interception. Alagarswamy et al. (2006) evaluated the ability of the CROPGRO–Soybean model to predict the responses of net leaf photosynthesis (A_L) and canopy photosynthesis (A_{can}) to photosynthetic photon flux (PPF) at different ambient [CO_2], and also compared the default leaf photosynthesis equations in CROPGRO with the full Farquhar equations for their ability to predict the response of A_L to [CO_2] and found them (leaf photosynthesis equations in CROPGRO) adequate for accurate crop simulations.

The CROPGRO model simulates processes such as vegetative and reproductive development which determine life cycle duration, duration of root and leaf growth, and onset and duration of reproductive organs such as pods and seeds. Crop C balance includes daily inputs from photosynthesis, conversion of C into crop tissues, C losses to abscised parts, and growth and maintenance respiration. The C balance routine also simulates leaf area expansion, growth of vegetative tissues, pod addition, seed addition, shell growth, seed growth, nodule growth, senescence, and carbohydrate mobilization (Boote et al., 2002).

The CROPGRO model template provides for species, ecotype, and cultivar traits to be defined in external read-in files for simulation of specific crops, making it easy to be adapted for simulating new crops without making changes in the program code (Jones et al., 2003). It is assumed that most of these processes in the soil–plant system remain constant across species and therefore lack of literature on specific processes for a specific crop of interest for modeling does not hinder development of a model for that crop. As a result, the CROPGRO model has been successfully adapted to simulate more than 10 crops including seven grain legumes: soybean [*Glycine max* (L.) Merr.], peanut (*Arachis hypogaea* L.), dry bean (*Phaseolus vulgaris* L.), chickpea (*Cicer arietinum* L.), cowpea (*Vigna unguiculata* L.), velvet bean (*Mucuna pruriens*), and faba bean, and nonlegumes such as tomato (*Lycopersicon esculentum* Mill.) and brachiaria grass (*Brachiaria decumbens* Stap.) (Jones et al., 2003).

The RZWQM2 is a process-oriented agricultural system model that integrates biological, physical, and chemical processes for predicting the impact of tillage, water, agricultural chemicals, and crop management practices on soil water, crop production, and water quality (Ahuja et al., 2000). The CERES and CROPGRO modules of DSSAT v4.0 (Jones et al., 2003) have been linked with the soil and N modules of RZWQM (Ma et al., 2005, 2006, 2009). Saseendran et al. (2009) adapted the CERES crop modules available in RZWQM2 to simulate spring triticale (*X Triticosecale* Wittmack), proso millet (*Panicum miliaceum* L.), and foxtail millet [*Setaria italica* (L.) Beauv.]. An earlier version of the RZWQM-DSSAT hybrid was successfully used for simulation and development of management practices for various cropping systems in the United States and elsewhere (Saseendran et al., 2007). The objective of this study was to adapt and evaluate the CROPGRO-faba bean model for simulation of spring canola in both RZWQM2 and DSSAT 4.0.

MATERIALS AND METHODS

Field Experiments

Data for this study were obtained from six canola water use/yield experiments conducted in 1993, 1994, 2005, and 2006 at the USDA-ARS Central Great Plains Research Station (40°9′ N, 103°9′ W, 1384 m) located 6.4 km east of Akron, CO. Management details for all six experiments are given in Table 1. Mean annual precipitation for the location is about 415 mm, of which 288 mm is received from May to September (Table 2). Precipitation received during the canola growing season (April through July) averages 244 mm but ranged between 136 and 265 during the growing seasons used in this study. During 1993 and 1994, two experiments were conducted. In the first experiment canola was grown under a rainout shelter (ROS). The second experiment used a line-source gradient irrigation (LSGI) system to impose water treatments.

The ROS experiments were conducted to determine canola production potential under the limited and variable precipitation (simulated through irrigation in the experiments) found in northeastern Colorado (Nielsen, 1997). Water stress timing effects on canola yield components were determined under a rainout shelter in 1993 and 1994, with water withheld during either the vegetative, reproductive, or grain-filling growth stage. The 15-wk growing season was divided into a 5-wk vegetative period, a 5-wk reproductive period, and a 5-wk grain-filling period, as determined by visual observations of canola development at Akron from previous years (D.C. Nielsen, unpublished data, 1992). The four irrigation treatments were (i) 234 mm applied in 15 equal weekly applications; (ii) no water applied during the 5 wk of vegetative development followed by 10 equal weekly applications totaling 234 mm; (iii) no water applied during the 5-wk reproductive period with 234 mm of irrigation divided evenly among the 5 vegetative weeks and the 5 grain-filling weeks; (iv) 234 mm of irrigation divided evenly among the first 10 wk of development with no water applied during the 5 grain-filling weeks.

The LSGI experiments were conducted in 1993, 1994, 2005, and 2006 to develop a water use-yield production function for canola grown using a line-source gradient irrigation system to

Table 1. Management details for four canola water use/yield studies conducted at Akron, CO.

Study designation	Year	Replications	Water treatments	Irrigation amounts	Irrigation method	Plot size	Row spacing	Variety	Planting date	Final population	Fertilizer
				mm		m by m	cm			plants ha^{-1}	kg N ha^{-1}
ROS†	1993	3	four growth stage timing treatments	234 for each treatment	flood	2.74 by 2.66	30	'Westar'	20 April	1,092,000	67
ROS	1994	3	four growth stage timing treatments	234 for each treatment	flood	2.74 by 2.66	30	'Westar'	7 April	1,092,000	67
LSGI	1993	4	four gradient irrigation treatments	42, 113, 202, 264	sprinkler	6.1 by 24.4	19	'Westar'	3 May	1,037,000	69
LSGI	1994	4	four gradient irrigation treatments	36, 118, 220, 263	sprinkler	6.1 by 24.4	19	'Westar'	22 April	1,037,000	94
LSGI	2005	4	four gradient irrigation treatments	0, 61, 134, 207	sprinkler	6.1 by 24.4	19	'Hyola'	8 April	630,000	56
LSGI	2006	4	four gradient irrigation treatments	0, 30, 67, 121	sprinkler	6.1 by 24.4	19	'Hyola'	20 April	630,000	56

† ROS = rainout shelter experiment; LSGI = line-source gradient irrigation experiment.

create variable water availability conditions. A diagram of the LSGI plot layout is given in Nielsen (2004).

In all six studies, crop water use (evapotranspiration) was calculated by the water balance method using soil water measurements, precipitation amounts, and irrigation catch gauge amounts, and assuming runoff and deep percolation were negligible (plot area slope was <0.5%, and amounts of growing season precipitation were generally small). Soil water measurements were made weekly in the ROS experiments and biweekly in the LSGI experiments using a neutron probe at soil depths of 15, 45, 75, 105, 135, and 165 cm. Leaf area index, plant height, and biomass (1 m of one row sampled) were also measured periodically during the growing season. The LAI measurements were made with the LAI-2000 Plant Canopy Analyzer (Li-Cor, Inc., Lincoln, NE). Biomass and LAI were not measured in the LSGI experiments in 1993 and 1994. However, grain yield and biomass were measured at plant maturity.

Adaptation of CROPGRO-Faba Bean Module for Canola Simulation in Root Zone Water Quality

To parameterize CROPGRO for canola in RZWQM2, we adopted the procedures recommended by Boote et al. (2002) for adapting the CROPGRO-dry bean model for simulation of faba bean. Boote et al. (2002) stated that the advantages of adapting a mechanistic process-oriented model like CROPGRO to a new crop included being able to use existing modular subroutines that describe the basic processes of photosynthesis, respiration, plant N and C balance, and soil water and N balance while also being able to use the weather handling and standard input-output file conventions of DSSAT.

The CROPGRO module simulates different crop species using external species, ecotype, and cultivar parameter files (Jones et al., 2003). The species file describes various plant physiological process sensitivities to environment, and the cultivar parameters describe cultivar differences in environmental effects on growth

Table 2. Precipitation received at the experimental site during 1993, 1994, 2005, and 2006, and long-term means (1908–2008). Data presented as annual and monthly totals, as well as total precipitation for the canola growing season (April–July) and the May through September period.

	1993	1994	2005	2006	1908–2008
			mm		
January	6	10	3	1	9
February	14	5	3	2	9
March	13	2	11	16	20
April	47	53	42	23	42
May	27	29	62	37	74
June	45	6	86	18	62
July	114	70	75	58	66
August	24	30	94	87	56
September	23	8	10	29	30
October	95	73	75	16	23
November	26	26	19	2	13
December	12	13	6	26	11
Annual	446	325	486	315	415
April–July	233	158	265	136	244
May–Sept.	233	143	327	229	288

and development. The ecotype parameters show how groups of cultivars differ with respect to life cycle duration and other plant growth processes including photosynthesis, respiration, leaf area growth, specific leaf area, and yield components. In this study, we developed the species, cultivar (genetic), and ecotype parameters for simulation of spring canola using the CROPGRO module with faba bean parameters as initial values.

Input Data for the Root Zone Water Quality Model

For simulations of an agricultural system, RZWQM2 needs detailed data on climate, soil, and crop management of the experimental site. All the input data used in this study were either measured in the field, or obtained from literature or the default database. Typical crop management data needed are planting and harvest dates, planting depth, row spacing, and plant population. Also, the amount, dates, and methods of irrigation, tillage, and fertilizer applications, if any, are required. These data were collected at the experiment site.

The minimum driving variables for RZWQM2 are daily solar radiation, maximum and minimum air temperature, wind speed, relative humidity, and precipitation (as break-point precipitation data; break-point precipitation data are pairs of time and cumulative precipitation values used to quantify rainfall intensity). Excepting break-point precipitation, all the above variables were measured at a weather station within 300 m of the experiment area. Daily precipitation was recorded in the plot area and we assumed daily precipitation to consist of storms of 120-min duration to create the required break-point precipitation data. In addition, the model also needs albedo for dry and wet soil, mature crop and residue, and average daily sunshine fraction for the hours in a day when the sun is above the horizon for potential evapotranspiration (PET) computations. The albedos were assumed to be 0.25, 0.20, 0.35, and 0.30, respectively (Ahuja et. al., 2000).

Soil physical and hydraulic properties for a silt loam soil as available in the RZWQM2 database from Rawls et al. (1982) were used for the simulations of the crop on the Weld silt loam soil in this study.

Model Parameterization and Calibration

To calibrate the CROPGRO model, the systematic approach described by Boote (1990) was followed. For accurate simulations, agricultural system models need to be calibrated for soil hydraulic and nutrient properties and plant growth parameters for the crops. We used the soil hydraulic and nutrient properties developed by Saseendran et al. (2009) for the site.

In the CROPGRO model, in addition to the species and ecotype parameters, 15 cultivar specific parameters (genetic coefficients) for defining the traits that differentiate between cultivars within a crop species are needed (Jones et al., 2003). Soil water, LAI, and biomass data measured at about weekly intervals, and grain yield at harvest collected in the 2005 irrigation experiments (four irrigation treatments) were used for calibrations of the cultivar specific coefficients. Additional data collected in 1993, 1994, and 2006 were used for model validation.

Development of Species-Specific Parameters

Parameters describing the processes of carbon and N budgets, leaf and root development, and phenology are specific to a crop species and are grouped in a species file. All the parameters related to nitrogen fixation processes were bypassed from the CROPGRO model as canola does not fix N.

In the CROPGRO model, temperature effects on physiological development rate, photosynthesis, and respiration are simulated by defining base and optimal temperatures, and equations to control the shapes of the curves used to affect nonoptimal temperature influences on plant processes. The specific equation shape (four point functions) for a process and its cardinal temperatures [base(FNGPT1), first optimum(FNGPT2), second optimum (highest) (FNGPT3), and maximum temperatures(FNGPT4)] are defined in the species file. These four parameters are used to define critical values of temperatures for the function to control canopy photosynthesis (TPGFAC) (Table 3). XLMAXT (provides base, optimum, and maximum temperature values over which the TEMPMX takes the values between 0.0 and 1.0) is used to compute the factor to control leaf photosynthesis (TEMPMX) (Table 3).

The cardinal temperatures Tbase, Toptimum1, Toptimum2, and Tmaximum are critical for growth stage simulations during vegetative development. Morrison et al. (1989) and Kiniry et al. (1995) reported 5°C as the base temperature for accumulating heat for growth of canola. Bunce (2008) reported observed good acclimation capacity to moderate temperatures (10–35°C) in *Brassica oleracea,* another species in the brassica family that canola belongs to. Polowick and Sawhney (1988) reported male and female sterility in canola growth under 32/26°C day/night temperatures. Vigil et al. (1997) reported stand losses when canola was planted in soils below 8°C, however the crop emerged at temperatures as low as 2°C. Angadi et al. (2000) observed a day/night temperature of 35/15°C injurious to reproductive organs of *Brassica napus* in growth chambers. Nanda et al. (1995) reported a base temperature of 5°C for leaf appearance in *Brassica napus*. Based on the available literature on response of canola to temperature, we calibrated the cardinal temperature parameters FNPGT and XLMAXT. The cardinal temperatures Tbase, Toptimum1, Toptimum2, and Tmaximum for vegetative development also have been calibrated (Table 3) (Fig. 1).

For simulations of photosynthesis using the 'canopy photosynthesis' routine of CROPGRO, the parameter KCAN (canopy light extinction coefficient, *k*, for daily photosynthetically active radiation, for equidistant plant spacing, modified when in-row and between row spacing are not equal) is needed for calculating the fraction solar radiation intercepted by the plant canopy based on the Beer–Lambert attenuation law. Andersen et al. (1996) estimated *k* for summer rape crops in the range of 0.7 to 1.0. Gabrielle et al. (1998b) found a value of 0.75 suitable for simulation of canola using the radiation use efficiency approach (RUE). For simulation of spring canola in the current study, we found a value of 0.75 was reasonable (Table 3).

For accurate simulations of leaf level photosynthesis in response to varying atmospheric CO_2 concentration levels using the modified Farquhar model in CROPGRO (Boote and Pickering, 1994), specification of the parameter CCMP, the canopy CO_2 compensation point, is critical as shown in the following equations:

$$\text{PRATIO} = \text{A0} + \text{CCMAX} \times [1 - e^{(-\text{CCK} \times \text{CO2})}] \quad [1]$$

Table 3. Species-specific parameters developed for simulation of canola with CROPGRO-faba bean parameters as a starting point.

Parameter	Value	Guidance from literature or calibration
KCAN- Canopy light extinction coefficient for daily PAR, for equidistant plant pacing, modified when in-row and between row spacing are not equal.	0.75	Gabrielle et al. (1998b).
CCMP- Canopy CO_2 compensation point (CO_2 at which daily gross photosynthesis is 0.0), mg/kg	72	Herath and Ormrod (1972)
FNPGT(I) Critical values of temperature for the functions to reduce canopy PG under nonoptimal temperatures (in function CURV)	5.00 20.0, 28.0, 40.0	Polowick and Sawhney (1988), Morrison et al. (1989), Bunce (2008)
XLMAXT- Temperature effects on maximum leaf photosynthesis (LMXREF).	0.0 5.0 28.0 29.0 40.0 60.0	Morrison et al. (1989), Bunce (2008), Vigil et al. (1997), Angadi et al. (2000), Nanda et al. (1995)
PCH2O Respiration loss due to storage/mobilization of CH_2O [kg(CH_2O)/kg(CH_2O)]	0.70	Calibrated.
PROLFI Maximum protein composition in leaves during growth with luxurious supply of N	0.244	Sidlauskas and Bernotas (2003)
PROLFG Normal growth protein composition in leaves during growth [kg(protein)/kg(leaf tissue)]	0.194	Sidlauskas and Bernotas (2003)
PROLFF- Minimum leaf protein composition after N mining (kg[protein]/kg[leaf])	0.092	Sidlauskas and Bernotas (2003)
NVSMOB Relative rate of N mining during vegetative stage to that in reproductive stage	0.25	Calibrated
YSTEM values- Partitioning fraction to stem at different V-stages (stages correspond to the number of leaf nodes on the main stem of the plant) (kg[stem]/kg[veg. plant])	0.06, 0.36, 0.20, 0.20, 0.30, 0.30, 0.43.	Calibrated
WTFSD Relative weight of seed compared to maximum (fraction)	0.90	Calibrated
SLAPAR Coefficient in exponential equation to reduce SLA as PAR increases (leaf curvature)	–0.045	Calibrated
TURSLA Water stress effects on leaf area expansion, factor.	1.20	Calibrated
SLAMAX The maximum specific leaf area (SLA) for new leaves when grown under low (nearly zero) radiation but optimum water and temperature for the standard cultivar. (cm^2/kg)	925	Calibrated
SENRTE Factor by which protein mined from leaves each day is multiplied to determine leaf senescence. [kg(leaf)/kg(protein loss)]	0.90	Calibrated
SENRT2 Factor by which leaf weight is multiplied to determine senescence each day after NR7 (day when 50% of the plants have yellowing or maturing pods) [g(leaf)]	0.25	Calibrated
SENDAY Maximum fraction of existing leaf weight which can be senesced on day N as a function of severe water stress 4 d earlier. [g(protein loss)]	0.26	Calibrated
T base, T optimum 1, T optimum 2, and T maximum for vegetative development.	1.0, 16.0, 25.0 and 40.0	Morrison et al. (1989), Bunce (2008), Vigil et al. (1997), Angadi et al. (2000), Nanda et al. (1995), Kiniry et al. (1995)
Node number on main stem and corresponding internode length (m) in pairs	0:0.11, 1:0.025, 4:0.036, 6:0.06, 8:0.082, 0:0.093, 14:0.087, 17:0.071, 22:0.049, 40:0.004.	Calibrated

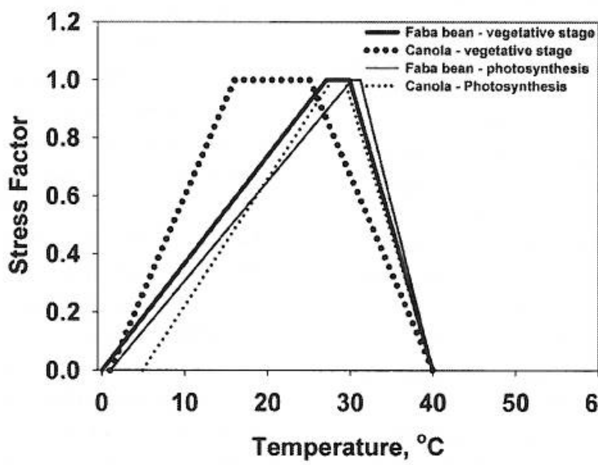

Fig. 1. Cardinal temperatures of faba bean modified for simulation of temperature effects on photosynthesis and vegetative growth stage of canola.

$$CCK = CCEFF/CCMAX \quad [2]$$

$$A0 = -CCMAX \times [1 - e^{(-CCK \times CCMP)}] \quad [3]$$

where PRATIO is the relative effect of CO_2 on canopy PG (factor to multiply PG computed at 330 $\mu L\ L^{-1}$ by), CCMAX is maximum daily canopy photosynthesis relative to photosynthesis at a CO_2 concentration of 330 $\mu L\ L^{-1}$, CCK is a computed exponent for the relationship between CO_2 and canopy photosynthesis, CCEFF is the relative efficiency of CO_2 assimilation used to adjust canopy photosynthesis with CO_2 concentrations.

Studies on CO_2 compensation points in canola are not available in the literature. However, Herath and Ormrod (1972) observed CO_2 compensation point variation between 65 and 90 mg kg^{-1} under various temperature and sulfur regimes in rape (*Brassica campestris* L.) plants. Considering their data and comparing simulated crop growth of canola with field measurements, we found that a CO_2 compensation point value of 72 mg kg^{-1} worked well for simulation of canola (Table 3).

Knowledge of N and protein composition of plant tissues is essential for simulations of growth respiration costs and ontogenical conversion costs of tissues (Godwin and Singh, 1998). As such, correct specification of parameters in these processes is essential for simulating N requirement for tissue growth and consequent seed (dry matter as well as oil) yields. Sidlauskas and Bernotas (2003) reported highest leaf N content of 5.57% N at fourth to fifth leaf stage declining to 1.02% N at seed development stage in canola. Based on this study and through comparison of simulations with measured growth data, the parameters PROLFI (maximum protein composition in leaves during growth with luxurious supply of N), PROLFG (normal growth protein composition in leaves during growth) and PROLF (minimum leaf protein composition after N mining) were calibrated as 0.244 g (protein)/g (leaf tissue), 0.194 g (protein)/g (leaf tissue) and 0.092 g (protein)/g (leaf tissue), respectively. Similarly NVSMOB (relative rate of N mining during vegetative stage to that in the reproductive stage) was calibrated as 0.25 (fraction). Plant respiration loss coefficient due to mobilization of CH2O (PCH2O) was calibrated to 0.70.

As there was no literature value for partitioning of dry matter to stem at different vegetative stages of growth of the canola plant (YSTEM), we calibrated the parameter by comparing simulated and measured plant height (Table 3). In the absence of measured data, similar calibrations were made to parameters: WTFSD (relative weight of seed compared to maximum), SLAMAX (maximum specific leaf area for new leaves when grown under low radiation but optimum water and temperature for the standard cultivar), SLAPAR (coefficient in exponential equation to reduce SLA as PAR increases), TURSLA (a factor used in the calculation of the factor TURFSL which applies water stress to specific leaf area of new leaf tissue growth), SENRTE (the amount of nonprotein vegetative mass abscised per gram of protein mobilized during grain fill), and SENRT2 (factor by which leaf weight is multiplied to determine senescence each day after physiological maturity) (Table 3). Boote et al. (2002) used a value of 0.8 kg kg^{-1} for SENTRE for simulation of faba bean using CROPGRO (a value of 1.0 kg kg^{-1} was used in the CROPGRO-dry bean model). We found a value of 0.9 kg kg^{-1} suitable for canola.

Plant canopy height and width affect light interception in the hedgerow canopy photosynthesis model used in CROPGRO (Boote and Pickering, 1994). In the model, the canopy height and width are simulated as functions of main-stem node number and internode length. These parameters are specified in the species file as look-up arrays of maximum potential internode length for successive nodes above the cotyledonary node. We calibrated these parameters to match the simulated crop height with measured data (Table 3).

Development of Ecotype Parameters

In CROPGRO, ecotype parameters are common to a group of cultivars in a species, including oil and protein content, growth phase durations (phenology), sensitivity to daylength, internode length, canopy width, leaf area and stem growth, seed numbers per pod, seed size, specific leaf area (SLA) and leaf photosynthetic rates. There are 19 parameters listed in the "ecotype file". A thorough review of literature was conducted for measured values of these parameters. However, we could find measured values for only four parameters out of the 19 (Table 4). Vigil et al. (1997) reported growing degree days (GDD) between 65 and 80 for emergence of spring canola planted 1-cm deep in pots in a Weld silt loam soil, at Akron, CO. Canola planted at the location in the month of April can take between 4 and 7 d to accumulate that many GDDs, depending on the weather. However, to achieve a close match between measured and simulated days to emergence we have calibrated the PL-EM (time between planting and emergence in photothermal days) to 5.0 photothermal days.

The parameter TRIFOL (rate of appearance of leaves on the main stem–leaves per photothermal day) simulates leaf development on the main stem of the canola plant. Nanda et al. (1995) observed a leaf appearance rate of 0.37 ± 0.07 leaves per day for canola. However, we used a value of 0.34 leaves per day for better simulations of canola growth.

Specification of the parameters SDPRO (fraction protein in seeds) and SDLIP (fraction oil in seeds) are critical for simulation of grain yield and quality, and oil quantity of canola. Hocking et al. (1997b) reported an average protein content of 18.6% in canola crops under dryland conditions in field experiments at Greenethorpe and Canowindra in the cereal belt of New South Wales, Australia. However, for simulations, data on the maximum protein contents under stress-free conditions are needed and for that reason we calibrated the parameter further by matching simulations with measurements and found a value of 20.1% (SDPRO) suitable for canola, very similar to the 18 to 20% protein content found by Brennan et al. (2000) for canola yield greater than 2600 kg ha^{-1} in Western Australia. Robertson et al. (2004) reported oil contents exceeding 40% in canola in response to various sowing dates in Australia. A calibrated seed oil content value of 45% (0.45 fraction) by weight for SDLIP for simulation of canola worked well in this study and was similar to values reported in the literature that ranged from 34 to 48% (Hocking et al., 1997a, Brennan et al., 2000; Nielsen, 1997).

Table 4. The ecological group-specific parameters developed for simulation of canola with CROPGRO-faba bean parameters as a starting point.

Parameter	Value	Guidance from literature or calibration
THVAR- Minimum rate of reproductive development under long days and optimal temperature	0.15	Calibrated
PL-EM Time between planting and emergence (V0) (thermal days)	5.0	Vigil et al. (1997).
EM-V1 Time required from emergence to first true leaf (V1), thermal days	4.0	Calibrated
V1-JU Time required from first true leaf to end of juvenile phase, thermal days	0.0	Calibrated
JU-R0 Time required for floral induction, equal to the minimum number of days for floral induction under optimal temperature and day lengths, photothermal days	2.0	Calibrated
PM06 Proportion of time between first flower and first pod for first peg (peanut only)	0.0	Calibrated
PM09 Proportion of time between first seed and physiological maturity that the last seed can be formed	0.48	Calibrated
LNGSH Time required for growth of individual shells (photothermal days)	17.5	Calibrated
R7-R8 Time between physiological (R7) and harvest maturity (R8) (thermal days)	09.0	Calibrated
FL-VS Time from first flower to last leaf on main stem (photothermal days)	44.00	Calibrated
TRIFOL Rate of appearance of leaves on the main stem (leaves per thermal day)	0.35	Nanda et al. (1995)
RWIDTH Relative width of this ecotype in comparison to the standard width per node (YVSWH) defined in the species file (*.SPE)	0.40	Calibrated
RHGHT Relative height of this ecotype in comparison to the standard height per node (YVSHT) defined in the species file (*.SPE)	1.2	Calibrated
THRESH The maximum ratio of (seed/(seed+shell)) at maturity. Causes seeds to stop growing as their dry weights increase until shells are filled in a cohort	70.0	Calibrated
SDPRO Fraction protein in seeds [kg(protein)/kg(seed)]	0.210	Hocking et al. (1997a), Hocking et al. (1997b)
SDLIP Fraction oil in seeds [kg(oil)/kg(seed)]	0.410	Brennan et al. (2000), Robertson et al. (2004)
R1PPO Increase in daylength sensitivity after R1 (CSDVAR and CLDVAR both decrease with the same amount) (h)	0.000	Calibrated
OPTBI Minimum daily temperature above which there is no effect on slowing normal development toward flowering (°C)	0.0	Calibrated
SLOBI Slope of relationship reducing progress toward flowering if TMIN for the day is less than OPTBI	0.000	Calibrated

Development of Cultivar Parameters

In the CROPGRO model, 15 parameters define cultivar specific traits of the crop (Table 5). As little information on these parameters was available in the experiments or literature, they were mostly calibrated through trial and error to match simulations with measurements. However, the parameters SIZLF [maximum size of full leaf, cm^2], WTPSD [maximum weight per seed, g], SDPDV [average seed per pod under standard growing conditions (no./pod)] were calibrated based on available literature information. Robertson et al. (2002) observed leaf areas up to 155 cm^2 in irrigated canola. However, to more accurately match LAI simulations with measured values, we used a calibrated value of 220 cm^2 for SIZLF.

Table 5. The cultivar specific parameters developed for simulation of canola with CROPGRO-faba bean parameters as a starting point.

Parameter	Value	Guidance from literature or calibration
CSDL Critical Short Day Length below which reproductive development progresses with no daylength effect (for short day plants) (hr)	24.00	Calibrated
PPSEN Slope of the relative response of development to photoperiod with time (positive for short-day plants) (1/hr)	–0.03	Calibrated
EM-FL Time between plant emergence and flower appearance (R1)(photothermal days)	16.50	Calibrated
FL-SH Time between first flower and first pod (R3) (photothermal days)	6.00	Calibrated
FL-SD Time between first flower and first seed (R5) (photothermal days)	13.00	Calibrated
SD-PM Time between first seed (R5) and physiological maturity (R7)(photothermal days)	22.79	Calibrated
FL-LF Time between first flower (R1) and end of leaf expansion (photothermal days)	55.00	Calibrated
LFMAX Maximum leaf photosynthesis rate at 30 C, 350 $\mu L\ L^{-1}\ CO_2$, and high light (mg CO_2/m^2-s)	0.90	Calibrated
SLAVR Specific leaf area of cultivar under standard growth conditions (cm^2/kg)	420.00	Calibrated
SIZLF Maximum size of full leaf (three leaflets) (cm^2)	220.00	Robertson et al. (2002)
XFRT Maximum fraction of daily growth that is partitioned to seed + shell	0.900	Calibrated
WTPSD Maximum weight per seed (g)	0.006	Hocking et al. (1997a); Chay and Thurling (1989)
SFDUR Seed filling duration for pod cohort at standard growth conditions (photothermal days)	24.00	Calibrated
SDPDV Average seed per pod under standard growing conditions (no./pod)	27.70	Chay and Thurling (1989), and Angadi et al. (2003)
PODUR Time required for cultivar to reach final pod load under optimal conditions (photothermal days)	9.00	Calibrated

Table 6. Measured (M) and simulated (S) [using CROPGRO-canola in RZWQM2] phenology for 2005 (line-source gradient irrigation experiment, LSGI), 2006 (LSGI), 1993(rainout shelter experiment, ROS), and 1994 (ROS) irrigation experiments at Akron, CO.

2005 (LSGI)†			2006 (LSGI)			1993 (ROS)			1994 (ROS)		
	DAP‡			DAP			DAP			DAP	
Stage	M	S	Stage	M	S	Stage	M	S	Stage	M	S
Planting (8 Apr.)			Planting (20 Apr.)			Planting (20 Apr.)			Planting (7 Apr.)		
Treatment 1											
Emergence	14	14	emergence	13	12	emergence	9	7	emergence	–	10
Flowering	59	58	flowering	46	47	flowering	52	46	flowering	56	53
First pod	66	65	first pod	50	54	first pod	64	58	first pod	65	62
First seed	73	73	first seed			first seed			first seed		
Harvested day	101	106	harvested day	97	93	harvested day	100	99	harvested day	95	94
Treatment 2											
Emergence	14	14	emergence	13	15	emergence	9	11	emergence	–	10
Flowering	59	56	flowering	46	49	flowering	52	49	flowering	56	53
First pod	66	63	first pod	50	55	first pod	64	59	first pod	65	60
First seed	73	71	first seed			first seed	–		first seed	–	69
Harvested day	104	109	harvested day	97	95	harvested day	100	95	harvested day	95	96
Treatment 3											
Emergence	14	14	emergence	13	11	emergence	9	7	emergence	–	10
Flowering	59	58	flowering	46	46	flowering	52	46	flowering	56	50
First pod	68	65	first pod	50	52	first pod	64	58	first pod	65	60
First seed	73	73	first seed			first seed	–		first seed	–	64
Harvested day	104	111	harvested day	97	94	harvested day	100	95	harvested day	95	92
Treatment 4											
Emergence	14	13	emergence	13	12	emergence	9	7	emergence	–	10
Flowering	59	58	flowering	46	47	flowering	52	46	flowering	62	56
First pod	68	64	first pod	50	53	first pod	64	62	first pod	65	59
First seed	73	72	first seed			first seed	–		first seed	–	64
Harvested day	104	111	harvested day	97	95	harvested day	100	104	harvested day	95	98

† Calibration data.

‡ DAP = days after planting.

Data on maximum possible seed weight under nonstressed conditions are lacking in literature. Nonetheless, Hocking et al. (1997b) reported seed weights up to 0.00347 g in dryland canola in Australia. Nielsen (1997) reported seed weights under water stress conditions ranging from 0.0027 to 0.0035 g per seed, with the lowest weights obtained when water stress occurred during grain filling. Chay and Thurling (1989) observed genetic potential up to 0.005 g per seed in *Brassica napus* breeding experiments. In our calibrations we found 0.006 g per seed appropriate for realistic simulations of grain yields.

Another important crop trait parameter is SDPDV (average seed per pod under standard growing conditions, numbers per pod). Angadi et al. (2003) reported, on average, grain numbers per pod in the main stem, and primary and secondary branches in the order of 18, 20, and 24, respectively. Chay and Thurling (1989) reported up to 27.7 seeds per pod in *Brassica napus*, which was used in this study. A single set of parameters calibrated as described above were found to be adequate for simulation of both cultivars ('Westar', 'Hyola') used in the experiments. Westar is an industry standard canola cultivar released by Agriculture Canada in 1982 and Hyola is a high yielding Polima CMS-based hybrid cultivar developed by Zenica/ICI (Brown et al., 2006).

Statistics for Model Calibration and Evaluations

We evaluated the simulation results using: (i) RMSE, Eq. [4], between simulated and observed values; (ii) the index of agreement (d) between measured and simulated parameters (Willmott, 1981) which varies between 0 (poor model) and 1 (perfect model), Eq. [5]; (iii) coefficient of determination (R^2), Eq. [6]; and relative error, Eq. [7].

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \qquad [4]$$

$$d = 1.0 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}\left(\left|P_i - O_{avg}\right| + \left|O_i - O_{avg}\right|\right)^2} \qquad [5]$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(O_i - O_{avg}\right)\left(P_i - P_{avg}\right)\right]^2}{\sum_{i=1}^{n}\left(O_i - O_{avg}\right)^2 \sum_{i=1}^{n}\left(P_i - P_{avg}\right)^2} \qquad [6]$$

$$\mathrm{RE} = \frac{(P_i - O_i)}{O_i} \times 100 \qquad [7]$$

where P_i is the *i*th simulated value, P_{avg} is the average of the simulated values, O_i is the *i*th observed value, O_{avg} is the average of the observed values, and n is the number of data pairs.

RESULTS AND DISCUSSION

Model Calibration

The collected data from the four irrigation treatments in 2005 were chosen for model calibration because the data collected in this year were more complete with less missing data on grain yield, biomass, plant height, soil water, and LAI.

Table 7. Evaluation statistics for CROPGRO-canola in Root Zone Water Quality Model (RZWQM2) simulations of total profile soil water, leaf area index (LAI), biomass, and plant height against measured values in the 1993, 1994, 2005, and 2006 canola irrigation experiments at Akron, CO.

Year-Treatment	Total profile(0–180 cm) soil water			LAI			Biomass			Plant height		
	RMSE†	R^2	d	RMSE	R^2	d	RMSE	R^2	d	RMSE	R^2	d
	$m^3 m^{-3}$						kg ha^{-1}			cm		
1993-ROS1‡	3.87	0.97	0.89	1.11	0.90	0.76	–	–	–	–	–	–
1993-ROS2	3.60	0.88	0.89	0.73	0.94	0.83	–	–	–	–	–	–
1993-ROS3	2.94	0.93	0.95	1.05	0.59	0.62	–	–	–	–	–	–
1993-ROS4	2.79	1.00	0.89	0.94	0.79	0.59	–	–	–	–	–	–
1993-LSGI1§	2.14	0.86	0.98	–	–	–	–	–	–	–	–	–
1993-LSGI2	2.76	0.56	0.99	–	–	–	–	–	–	–	–	–
1993-LSGI3	3.10	0.92	0.99	–	–	–	–	–	–	–	–	–
1993-LSGI4	1.41	0.72	1.00	–	–	–	–	–	–	–	–	–
1994-ROS	4.33	0.99	0.86	1.15	0.65	0.83	–	–	–	–	–	–
1994-ROS2	6.21	0.99	0.79	1.38	0.60	0.86	–	–	–	–	–	–
1994-ROS3	5.03	0.96	0.80	1.28	0.58	0.74	–	–	–	–	–	–
1994-ROS4	3.90	0.96	0.80	1.59	0.78	0.73	–	–	–	–	–	–
2005-LSGI1¶	2.45	0.95	0.84	0.80	0.78	0.93	836	0.85	0.94	10	0.92	0.96
2005-LSGI2¶	1.91	0.96	0.94	0.81	0.79	0.94	604	0.94	0.94	11	0.92	0.96
2005-LSGI3¶	1.02	0.90	0.97	0.77	0.89	0.93	341	0.98	0.99	9	0.94	0.97
2005-LSGI4¶	2.14	0.78	0.93	0.53	0.95	0.98	396	0.96	0.95	9	0.94	0.95
2006-LSGI1	3.68	0.63	0.71	0.42	1.00	0.77	463	0.92	0.59	8	0.91	0.94
2006-LSGI2	3.99	0.77	0.73	0.15	1.00	0.97	903	0.96	0.55	7	0.90	0.95
2006-LSGI3	4.05	0.90	0.77	0.81	1.00	0.89	510	0.95	0.89	9	0.86	0.96
2006-LSGI4	5.84	0.95	0.78	0.61	1.00	0.95	777	0.93	0.95	13	0.78	0.94

† RMSE = root mean square error, d = index of agreement, and R^2 = coefficient of determination.

‡ ROS1, ROS2, ROS3, and ROS4 are irrigation treatments under a rainout shelter.

§ LSGI1, LSGI2, LSGI, and LSGI4 are irrigation treatments under a line-source gradient irrigation system.

¶ Calibration data.

Simulations of plant emergence were within 1 d of observed emergence across the four irrigation treatments (Table 6). Simulated flowering time was off by 1 to 3 d, first pod by 1 to 4 d, first seed by 0 to 2 d, and harvest maturity by 3 to 5 d.

Soil water simulations in individual soil layers (2005) had RMSEs ranging from 0.024 to 0.031 $m^3 m^{-3}$ (data not shown). The RMSEs of total soil profile (180 cm) water storage ranged from 1.02 to 2.45 cm in the four irrigation treatments of 2005 (Table 7). The d values between measured and simulated data were between 0.84 and 0.97, providing confidence in soil water simulation during canola growth. Simulations of LAI, plant heights, and biomass at about biweekly intervals had RMSEs ranging from 0.53 to 0.81 $m^2 m^{-2}$ (Fig. 2), from 9 to 11 cm (Fig. 3), and from 341 to 836 kg ha^{-1} (Fig. 4), respectively. The LAI simulations were sufficiently accurate with d ranging from 0.93 to 0.98, and R^2 ranging from 0.78 to 0.95. Biomass simulations were also reasonable with d and R^2 between 0.94 and 0.99, and between 0.85 and 0.98, respectively. Plant height simulations showed relatively larger errors with RMSEs between 9 and 11 cm and d values between 0.95 and 0.97. Grain yield simulations in the four irrigation treatments of the 2005 LSGI calibration set departed from the measured data between –13 and 9% (Fig. 5). Simulations of grain yield had RMSE of 102 kg ha^{-1} and d of 0.87 (data not shown).

Measured data on seed oil and protein contents were not available for comparison in 2005. However, the simulated seed oil contents at harvest were between 44 and 45%, which were within the literature reported values of seed oil contents from 34 to 48% (Brennan et al., 2000; Robertson et al., 2004) and those measured in the experiments (between 34 and 45%) in 1993 and 1994 (Table 8). Simulated seed protein contents were between 20 and 21% across irrigation treatments, which are slightly higher than the reported protein content of 18.6% by Hocking et al. (1997b) but similar to that reported by Brennan et al. (2000). Hocking et al. (1997b) reported seed weights between 0.00280 to 0.00347 g in canola, which are in agreement with simulated seed weights between 0.0031 and 0.0033 g in the four irrigation treatments.

Model Evaluation

Line-Source Gradient Irrigation Experiments in 2006

The calibrated model was first evaluated for canola grown in 2006, which was a continuation of the 2005 study. Crop phenology was simulated reasonably well with deviations of days to emergence within 1 to 2 d, flowering within 1 to 3 d, first pod within 1 to 5 d, and harvest maturity within 2 to 4 d from measured data across the four irrigation treatments (Table 6) (in the experiment harvest day only was reported, as such this may not accurately represent the physiological maturity growth stage). Soil water, evapotranspiration (estimated from soil water balance), LAI, crop height, biomass, and grain yield (data not shown) in the 2006 crop season were reasonably well simulated (Table 7). The RMSEs of total profile (180 cm) soil water simulations were between 3.68 and 5.84 cm across the four irrigation treatments. Soil water simulations in terms of RMSE in various soil layers across treatments ranged from 0.029 to 0.046 $m^3 m^{-3}$. Across treatments, the R^2 and d of total profile water contents were between 0.63 and 0.95, and between 0.71 and 0.78, respectively(Fig. 6).

Leaf area index measurements in the experiments were only made in the beginning of the season and therefore the statistics

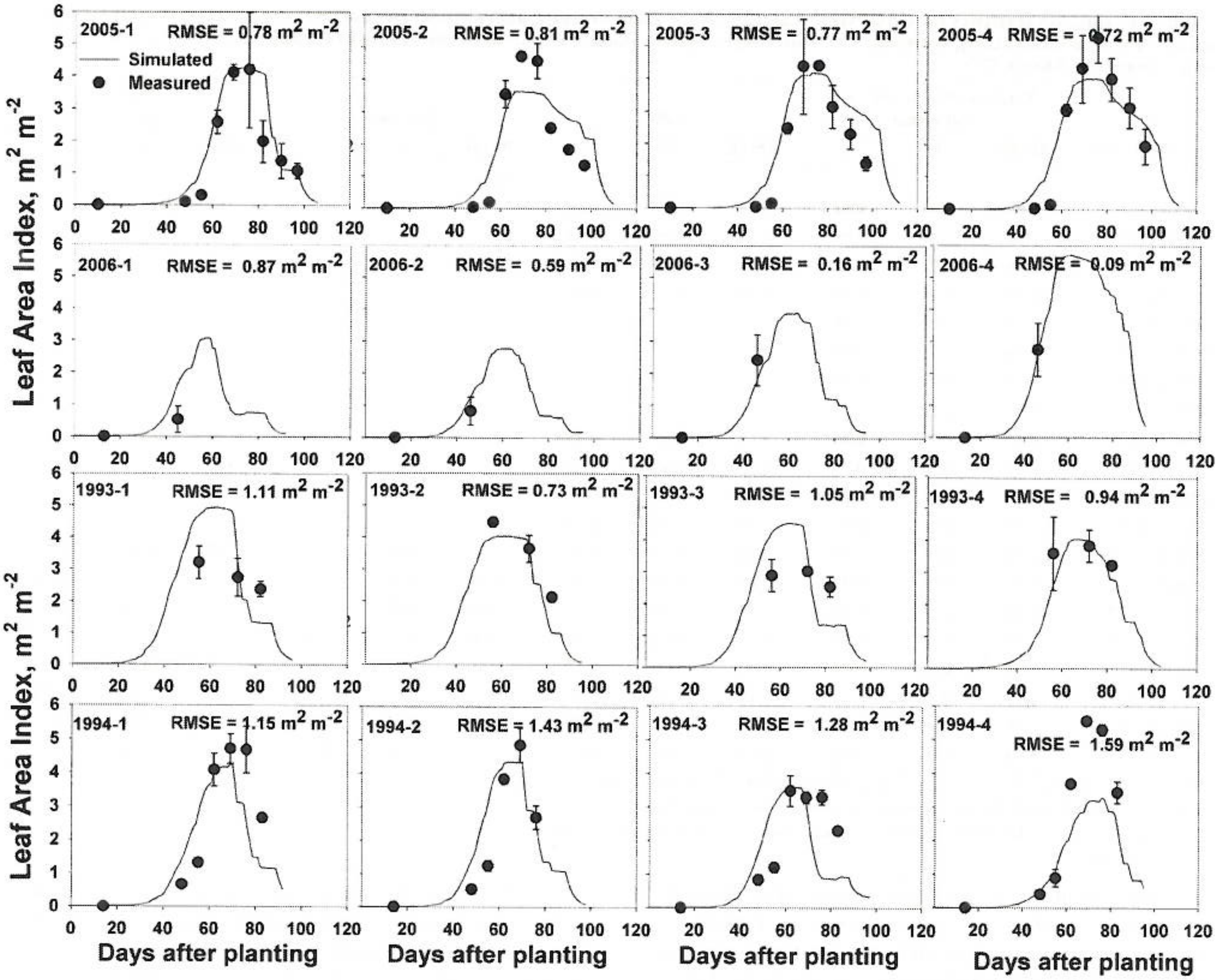

Fig. 2. Comparison of measured and simulated canola leaf area index using CROPGRO-canola in Root Zone Water Quality Model (RZWQM2) in response to four irrigation treatments each in 1993 and 1994 rainout shelter experiments, and 2005 (calibration set) and 2006 line-source gradient irrigation experiments. Error bars indicate one standard deviation of the mean.

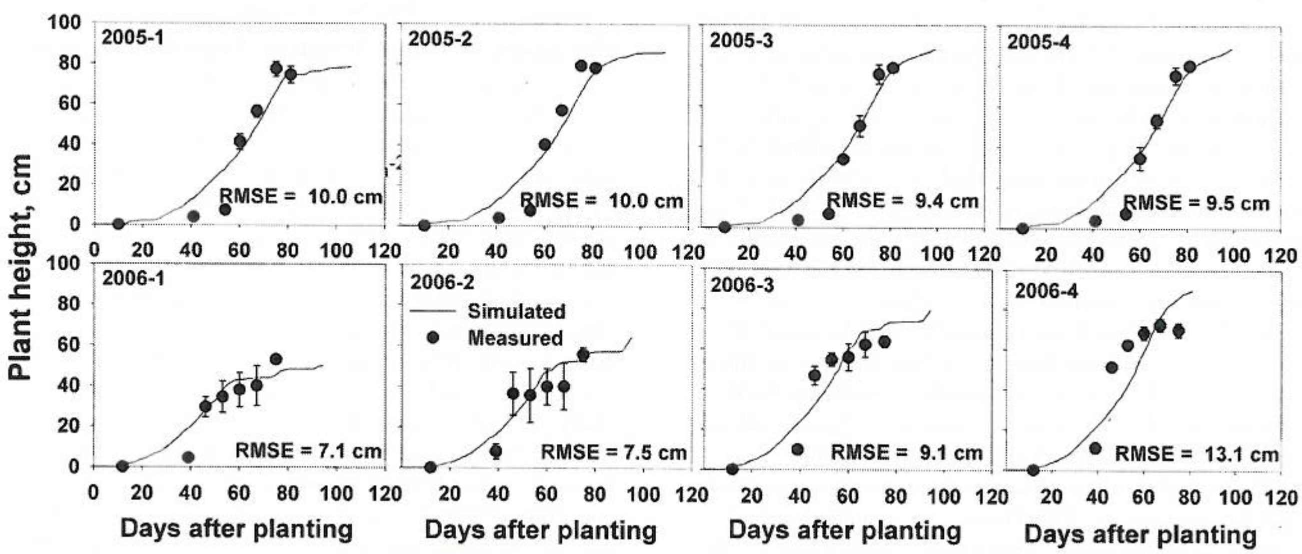

Fig. 3. Comparison of measured and simulated canola plant height using CROPGRO-canola in Root Zone Water Quality Model (RZWQM2) in response to four irrigation treatments each in 2005 (calibration set) and 2006 line-source gradient irrigation experiments. Error bars indicate one standard deviation of the mean.

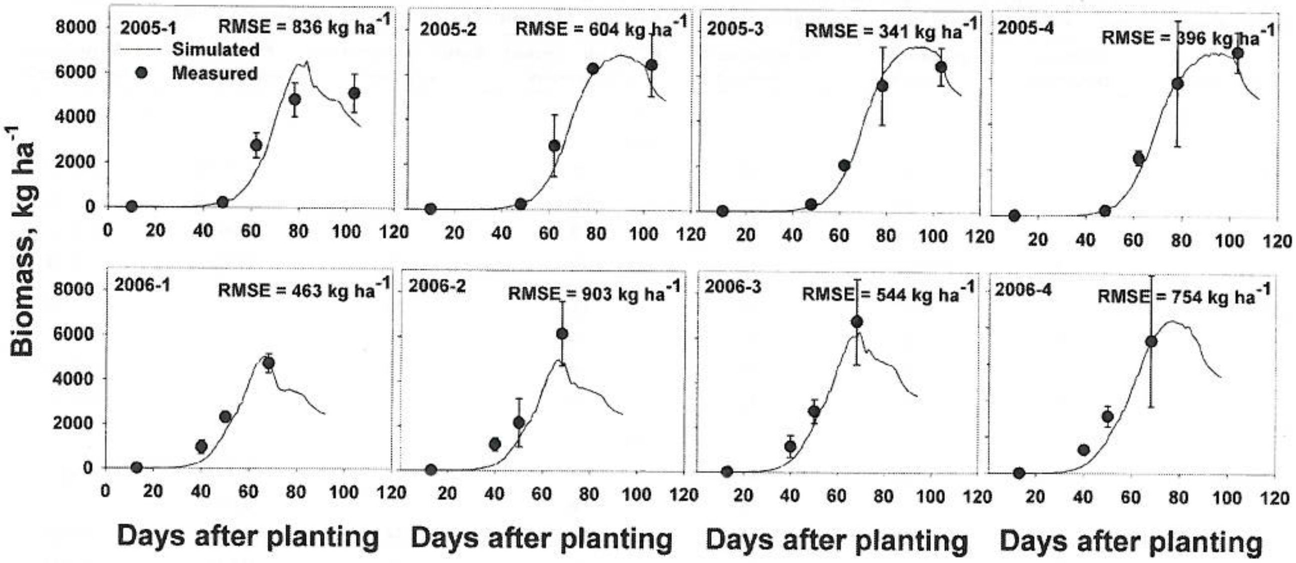

Fig. 4. Comparison of measured and simulated canola biomass using CROPGRO-canola in Root Zone Water Quality Model (RZWQM2) in response to four irrigation treatments each in 2005 (calibration set) and 2006 line-source gradient irrigation experiments. Error bars indicate one standard deviation of the mean.

calculated from the data are not reliable (Fig. 2). However, across the four irrigation treatments, LAI simulations had RMSEs ranging from 0.15 to 0.81 $m^2 m^{-2}$, and d from 0.77 to 0.95 (Table 7, Fig. 2). Plant heights were simulated with RMSEs between 8 and 13 cm, R^2 between 0.78 and 0.91, and d between 0.94 and 0.96 (Fig. 3).

Biomass and grain yields in response to the four irrigation treatments were fairly well simulated with biomass R^2 and d values ranging from 0.92 to 0.96 and from 0.55 to 0.95, respectively (Table 7, Fig. 4). Biomass was consistently underestimated before 60 d after planting. The RMSE values for biomass simulation ranged from 463 to 903 kg ha^{-1}. The model exhibited an inability to accurately capture severe water stress effects on yield when irrigation was low. While water stress in the low irrigation treatment resulted in no actual harvested grain yield, the model simulated 328 kg ha^{-1} (Fig. 5) In the treatment with 4.0 cm irrigation, the model simulated 683 kg ha^{-1} when the measured amount was 228 kg ha^{-1}. In the 7.9 and 13.1 cm water treatments, the model simulated grain yield better with 891 and 1613 kg ha^{-1} against the measured values of 724 and 1801 kg ha^{-1}.

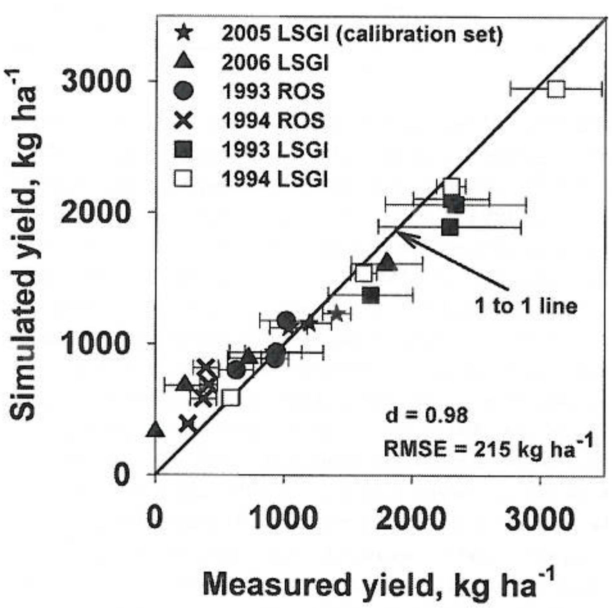

Fig. 5. Comparison of measured and simulated canola grain yield using CROPGRO-canola in Root Zone Water Quality Model (RZWQM2) in response to four irrigation treatments each in 1993, 1994, 2005 (calibration set), and 2006. Data in 1993 and 1994 consisted of treatments grown under both a rainout shelter (ROS) and a line-source gradient irrigation (LSGI) system. Error bars indicate one standard deviation of the mean.

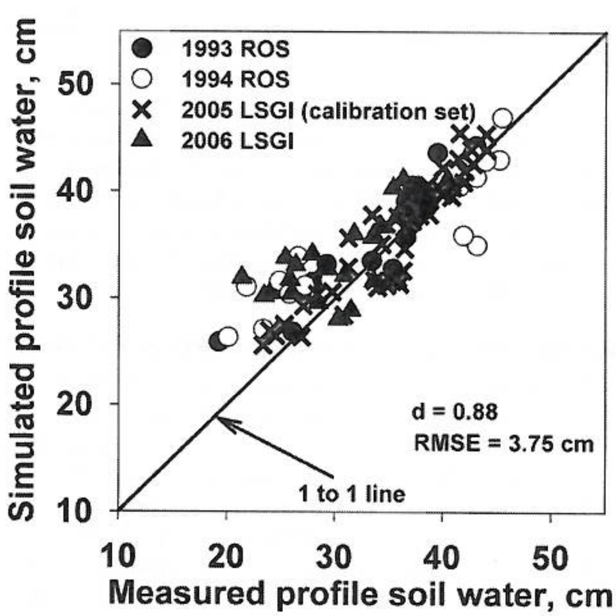

Fig. 6. Comparison of measured and simulated total soil profile water under canola using CROPGRO-canola in RZWQM2 in response to four irrigation treatments each in 1993 and 1994 (under a rainout shelter (ROS), and in 2005 (calibration set) and 2006 (under a line-source gradient irrigation (LSGI) system).

Table 8. Measured and simulated [using CROPGRO-canola in Root Zone Water Quality Model, RZWQM2] canola grain quality parameters (oil and protein content and seed weight). RE = relative error [(simulated-measured)/measured × 100].

Experiment†	Irrigation treatment	Measured oil content	Simulated oil content	RE of oil content simulations	Simulated protein content	Measured seed weight	Simulated seed weight
				–%–			–g–
				1993			
ROS	1	36	43	19	21	0.0032	0.0031
	2	34	43	26	20	0.0027	0.0032
	3	36	43	19	22	0.0034	0.0031
	4	35	42	20	20	0.0029	0.0033
LSGI	1	37	43	16	20	–	0.0032
	2	39	42	8	20	–	0.0031
	3	39	42	8	20	–	0.0033
	4	40	42	5	21	–	0.0032
				1994			
ROS	1	38	43	13	22	0.0029	0.0032
	2	37	44	18	21	0.0027	0.0031
	3	39	43	10	24	0.0030	0.0032
	4	39	43	10	21	0.0032	0.0034
LSGI	1	39	43	10	26	–	0.0031
	2	42	44	5	20	–	0.0033
	3	44	43	–2	20	–	0.0031
	4	45	43	–4	20	–	0.0032
				2005			
LSGI	1	–	45	–	21	–	0.0033
	2	–	44	–	20	–	0.0032
	3	–	44	–	20	–	0.0032
	4	–	44	–	20	–	0.0031
				2006			
	1	–	43	–	21	–	0.0032
	2	–	43	–	20	–	0.0033
	3	–	44	–	20	–	0.0035
	4	–	44	–	21	–	0.0035

† ROS = rainout shelter, LSGI = line-source gradient irrigation.

Simulated seed oil contents were between 43 and 44%, which was comparable with measurements in 1993 and 1994 (Table 8) and as reported in the literature (Brennan et al., 2000; Robertson et al., 2004). Simulated seed weight ranged from 0.0032 to 0.0035 g, and seed protein contents varied between 20 and 21% (comparable to values reported by Hocking et al. [1997b] and Brennan et al. [2000]).

Rainout Shelter Experiments in 1993 and 1994

Deviations in simulated plant emergence were by 1 to 3 d, flowering by 1 and 4 d, first pod by 1 and 5 d, and harvest maturity was off by 1 to 6 d. Timing of irrigation or water stress did not affect either measured or simulated canola yield both in 1993 and 1994. Measured yield among treatments ranged from 629 to 1018 kg ha^{-1} in 1993, and from 215 to 412 kg ha^{-1} in 1994. Corresponding simulations ranged from 801 and 1177 kg ha^{-1} in 1993, and 389 and 818 kg ha^{-1} in 1994. The d values and R^2 of yield simulations were 0.82 and 0.61, respectively in 1993, and 0.32 and 0.77, respectively in 1994

Simulated LAI had RMSEs between 0.73 and 1.11 m^2 m^{-2} in 1993, and between 1.15 and 1.59 m^2 m^{-2} in 1994 (Table 7) (Fig. 2). For LAI in 1993, the R^2 and d values were between 0.59 and 0.94, and between 0.59 and 0.83, respectively, and in 1994, R^2 ranged between 0.58 and 0.78, and d ranged between 0.73 and 0.86. Soil water simulations showed higher degree of error in 1993 and 1994 ROS experiments compared with other experiments in 2005 and 2006 (Table 7). Simulations of total profile soil water showed RMSEs between 2.79 and 6.21 cm with R^2 between 0.88 and 1.00, and d index between 0.79 and 0.95.

In 1993, measured seed oil content ranged between 34 and 36%, and in 1994 between 37 and 40% (Table 8). In line with these measured values, simulated seed oil contents in 1993 were between 42 and 43% (RMSE between 19 and 26%), and in 1994 between 43 and 44% (RE between 10 and 13%). However, the model failed to simulate the higher oil content in 1994 than in 1993. Simulated seed weights ranged between 0.0031 and 0.0034 g, and were comparable with the measured range of 0.027 to 0.032 g (Table 8). Simulated seed protein contents were between 20 and 24%, and are close to the 18.6% reported by Hocking et al. (1997b).

Line-Source Gradient Irrigation Experiments in 1993 and 1994

Data collected from these plots included soil water at about biweekly intervals during the 1993 crop season, and final grain

Table 9. Measured (M) and simulated (S) [using CROPGRO-canola in DSSAT] phenology for 2005 (line-source gradient irrigation experiment, LSGI), 2006 (LSGI), 1993 (rainout shelter experiment, ROS) and 1994 ROS) irrigation experiments at Akron, CO.

2005 (LSGI)†			2006 (LSGI)			1993 (ROS)			1994 (ROS)		
Stage	DAP‡		Stage	DAP		Stage	DAP		Stage	DAP	
	M	S		M	S		M	S		M	S
Planting (8 April)			Planting (20 April)			Planting (20 April)			Planting (7 April)		
					Treatment 1						
Emergence	14	9	emergence	13	10	emergence	9	7	emergence	–	14
Flowering	59	54	flowering	46	46	flowering	52	46	flowering	56	53
First pod	66	62	first pod	50	52	first pod	64	59	first pod	65	59
First seed	73	70	first seed	–	60	first seed	–	62	first seed	–	67
Harvested day	101	102	harvested day	92	90	harvested day	100	99	harvested day	95	98
					Treatment 2						
Emergence	14	9	emergence	10	7	emergence	9	11	emergence	–	14
Flowering	59	54	flowering	46	46	flowering	52	49	flowering	56	55
First pod	66	62	first pod	50	53	first pod	64	59	first pod	65	61
First seed	73	70	first seed	–	60	first seed	–	62	first seed	–	69
Harvested day	104	106	harvested day	97	96	harvested day	100	96	harvested day	95	98
					Treatment 3						
Emergence	14	9	emergence	13	10	emergence	9	7	emergence	–	14
Flowering	59	54	flowering	46	46	flowering	52	46	flowering	56	55
First pod	68	62	first pod	50	53	first pod	64	59	first pod	65	61
First seed	73	74	first seed	–	60	first seed	–	62	first seed	–	69
Harvested day	104	109	harvested day	97	95	harvested day	100	95	harvested day	95	97
					Treatment 4						
Emergence	14	9	emergence	13	7	emergence	9	11	emergence	–	14
Flowering	59	54	flowering	46	43	flowering	52	49	flowering	62	55
First pod	68	62	first pod	50	53	first pod	64	59	first pod	65	61
First seed	73	70	first seed	–	60	first seed	–	62	first seed	–	69
Harvested day	104	109	harvested day	97	98	harvested day	100	104	harvested day	95	99

† Calibration data.

‡ DAP = days after planting.

yield in both years. Profile soil (180 cm) water storage in 1993 was well simulated with RMSEs between 1.41 cm and 3.10 cm (Table 7). The R^2 and d of profile soil water storage simulations were between 0.56 and 0.92, and between 0.98 and 1.00, respectively. Simulated grain yields responded to the four irrigation levels well and deviated from measurements by −8 to −18% with a d value of 0.67 and R^2 of 0.93 in 1993, and by 0 and −5% with d of 0.99 and R^2 of 0.99 in 1994 (Fig. 5).

There were no measurements of LAI, biomass, or plant height in this experiment. Simulated seed weights ranged between 0.0031 and 0.0033 g per seed across treatments in the two crop seasons (1993 and 1994) (Table 8). Simulated seed oil contents were between 42 and 44% with REs between −4 and 10%. Simulated seed protein contents ranged between 20 and 26%.

Performance of CROPGRO-Canola in DSSAT

As the above results indicated, using the RZWQM2 soil water and N routines with the CROPGRO-canola model developed in this study reasonably simulated the spring canola experiments conducted at Akron, CO in 1993, 1994, 2005, and 2006 under various levels of water availability. It may be of interest to some model users to see how CROPGRO-canola performs within DSSAT 4.0. Therefore, we repeated the above simulations using CROPGRO-canola within DSSAT 4.0 keeping all the parameters and calibrations unchanged. In general, we found that the canola model developed can simulate the above experiments with similar accuracy in DSSAT as well. For brevity, we present only the simulations of phenology, LAI, biomass, and grain yield as examples of the simulations (Table 9 and Fig. 7–9). Across the 1993, 1994, 2005, and 2006 crop seasons with a total of 24 irrigation treatments (including the ROS experiments in 1993 and 1994), simulated growth stages deviated from the measured data by 2 to 6 d for plant emergence, 0 to 7 d for flowering, 2 to 6 d for first pod, 1 to 3 d for first seed and 1 to 5 d for maturity (Table 9). RMSEs of simulations of LAI in various irrigation treatments in 2005 and 2006 were between 0.48 and 1.13 $m^2 m^{-2}$ (Fig. 7). The LAI simulations in the ROS experiments in 1993 and 1994 showed higher deviations from measured (between 0.56 and 2.16 $m^2 m^{-2}$). Biomass simulations had RMSEs between 525 and 1024 kg ha^{-1} with d between 0.93 and 0.99 (Fig. 8). Grain yield simulations (pooled data for all treatments and years) showed an RMSE of 228 kg ha^{-1} and d of 0.97 (Fig. 9).

CONCLUSIONS

In the study, we adapted the existing CROPGRO-faba bean module to simulate spring canola with both RZWQM2 and DSSAT4.0 using available information on the various crop growth and development processes found in existing literature. However, we encountered lack of experimental data for defining many of the model parameters. In those situations, we calibrated the parameters available in the CROPGRO-faba bean model for simulation of canola. Overall, across irrigation treatments and crop seasons, simulations of biomass, LAI, grain yield, soil

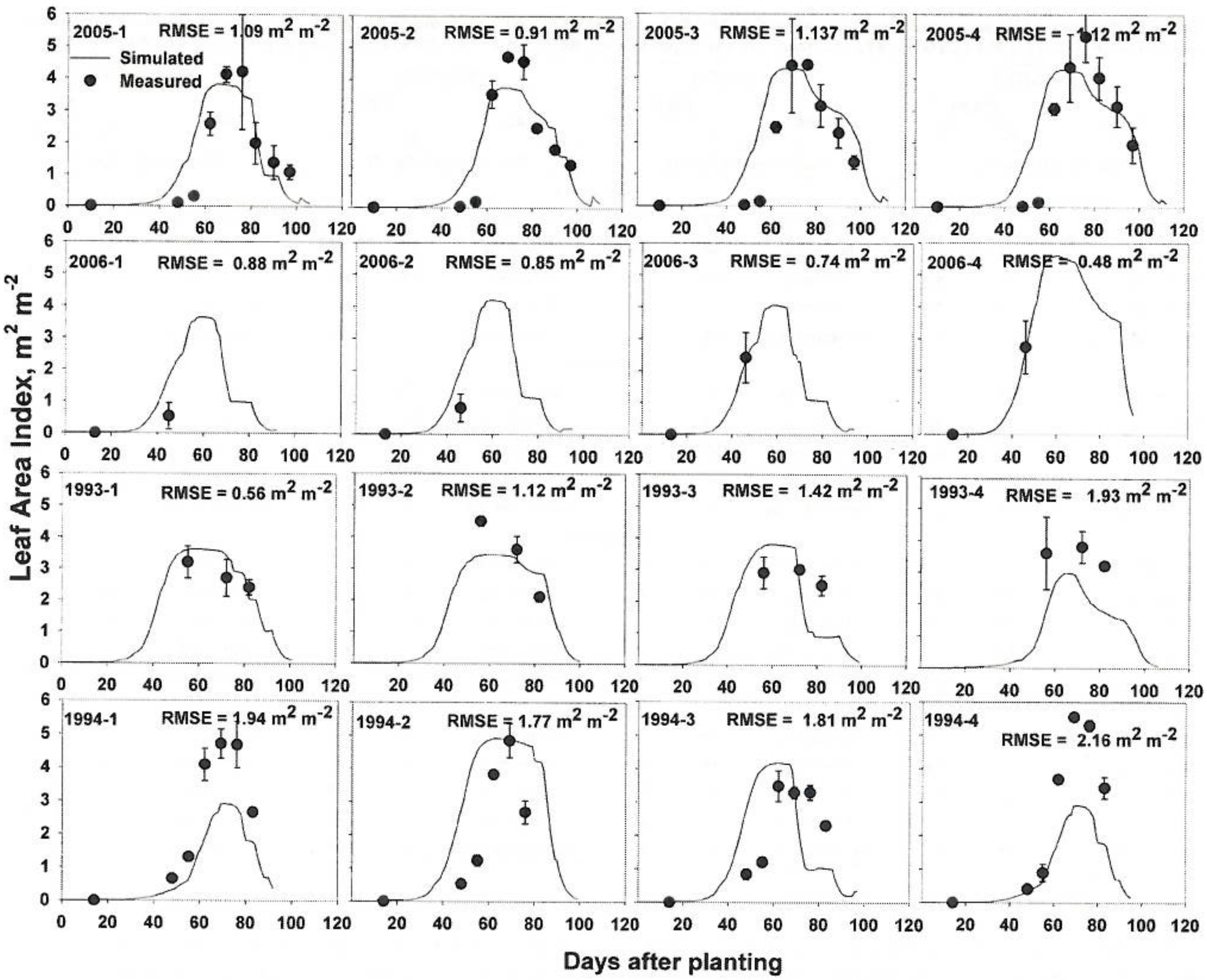

Fig. 7. Comparison of measured and simulated canola leaf area index using CROPGRO-canola in Decision Support System for Agrotechnology Transfer (DSSAT 4.0) in response to four irrigation treatments each in 1993 and 1994 rainout shelter experiments, and 2005 (calibration set) and 2006 line-source gradient irrigation experiments. Error bars indicate one standard deviation of the mean.

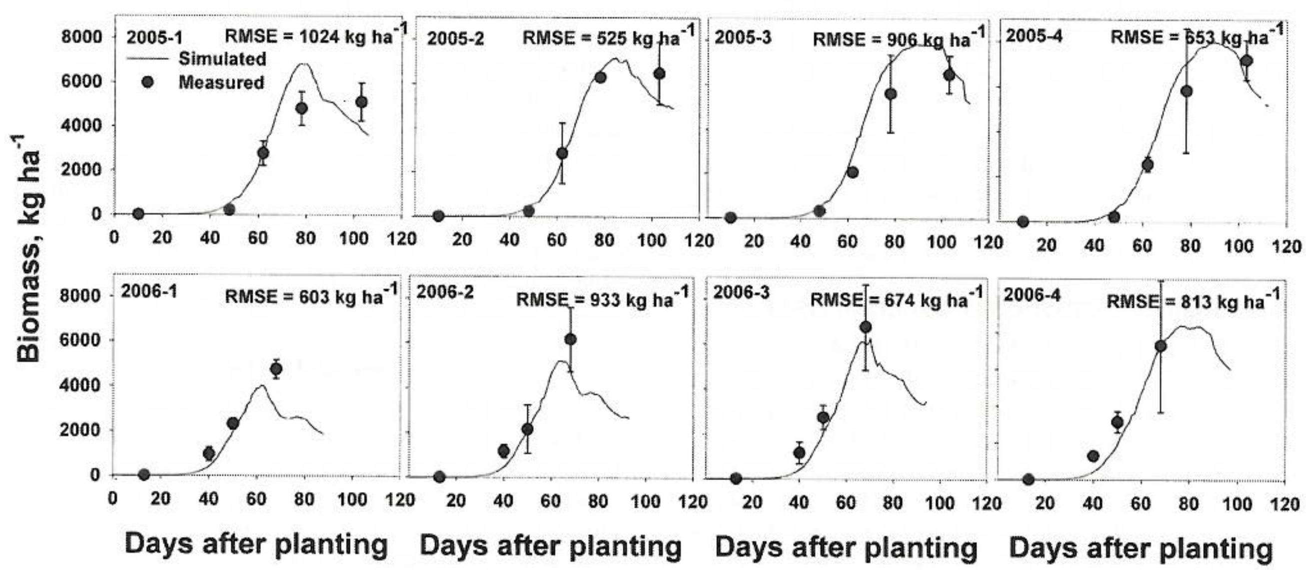

Fig. 8. Comparison of measured and simulated canola biomass using CROPGRO-canola in Decision Support System for Agrotechnology Transfer (DSSAT 4.0) in response to four irrigation treatments each in 2005 (calibration set) and 2006 line-source gradient irrigation experiments. Error bars indicate one standard deviation of the mean.

water, and ET were reasonable. A high degree of correspondence between measured and simulated results within both RZWQM2 and DSSAT 4.0 demonstrated that the CROPGRO model was adequately parameterized for canola. Accurate simulations of growth (e.g.: LAI, biomass, and grain yield) and development (growth stages) of the crop showed that the model has potential as a tool for development of decision support systems for canola management and for evaluation of canola as a potential alternative crop across the central Great Plains region. Further studies on simulating the crop across locations with contrasting climates can help in fine-tuning the model parameters developed and thereby increasing confidence in the model. Additional changes of the model, including accounting for vernalization, will be needed for simulations of winter canola.

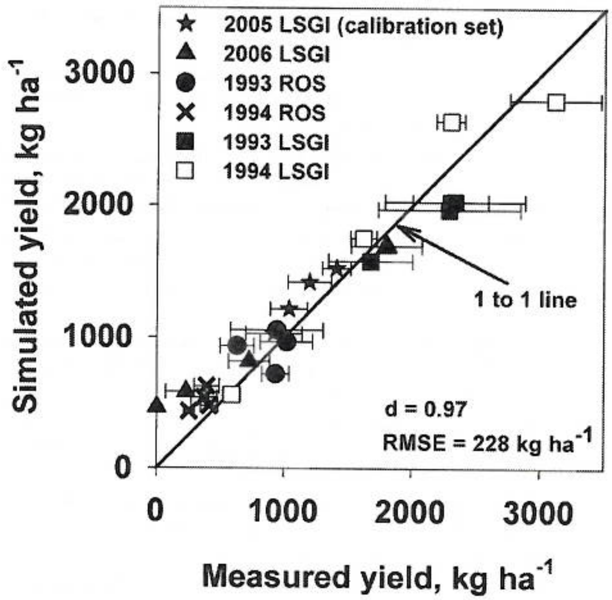

Fig. 9. Comparison of measured and simulated canola grain yield using CROPGRO-canola in Decision Support System for Agrotechnology Transfer (DSSAT 4.0) in response to four irrigation treatments each in 1993, 1994, 2005 (calibration set), and 2006. Data in 1993 and 1994 consisted of treatments grown under both a rainout shelter (ROS) and a line-source gradient irrigation (LSGI) system. Error bars indicate one standard deviation of the mean.

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