Identification of weak links in production technology for bridging the canola yield-gap in Punjab, Pakistan

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**Abstract**

Understanding the reasons for the yield gap between potential and actual yield can provide insights for enhancing canola production by adapting measures for ensuring food security. The canola yield gap under different management practices (e. g., water, nitrogen, N-, and sowing dates) was quantified using research trials that were conducted at on-station and historical data (1980-2016) and the CROPGRO-Canola model for Punjab, Pakistan. The integrated approach revealed that low inputs of N, the amount of irrigation, sowing date, and the use of seeds from home stocks were the principal causes for a low yield. The CROPGRO-Canola model was able to simulate the canola yield from research trials (R2 = > 0.90) and farm survey data (R2 = 0.63). The average yield gap between potential (YP), N-limited (YNL), water-limited (YWL), N- and water-limited (YNWL), and overall farmer field yield (YOFF) was 50%, 46%, 62%, and 72%, respectively. The yield-gap with achievable yield (YA) for YNL, YWL, YNWL, and YOFF was 34%, 28%, 49%, and 63%, respectively. Overall, the results showed that a high canola yield for farmers’ fields can be obtained by selecting appropriate varieties and sowing dates with N rate of 120 kg/ha and efficient irrigation management. However, further studies are necessary to fully comprehend the underlying causes for the low actual yield and the high yield variability of farmers’ fields.

**Keywords:** Achievable yield, CSM-CROPGRO-Canola, Crop simulation, Oilseed, Potential yield DSSAT

**Introduction**

Canola (*Brassica napus* L.), rapeseed/mustard (*Brassica rapa* L.), sunflower (*Helianthus annus* L.), and cotton (*Gossypium hirsutum* L.) are the major oilseed crops in Pakistan. Pakistan grows these oilseed crops on 3.32 x 106 ha, producing 3.80 x 106 t of grain yield and 0.57x 106 t of oil yield. Most of the oil produced is dedicated to meet the country’s internal needs. However, Pakistan has to import edible oil to satisfy its increasing domestic consumption (Govt. of Pakistan, 2018; Noreen *et al*., 2016; Ahmad *et al*., 2017a, b; Tariq *et al*., 2018). The average canola grain yield of 0.95 t/ha in Pakistan is very low compared to other canola-producing countries (Mahmood *et al*., 2012; Noreen *et al*., 2016). This is mainly due to poor farmer management that results in a large gap with attainable yield. Factors such as management practices, genotype, and environment determine crop yield. Understanding such factors can help in determining the magnitude of the yield-gap between attainable and farmer yield (Anderson *et al*., 2016; Dias and Sentelhas, 2018). For example, yield-gap analysis can help design guiding research and developing policies seeking to progress the livelihoods of resource-limited farmer communities. Yield-gap analysis might support site-specific recommendations aiming at developing sustainable practices within farming communities to better cope with in-season weather-related shocks that affect attainable yields (van Ittersum *et al*., 2013; Robertson *et al*., 2016). Yield-gap estimations can be obtained from field trials designed to minimize yield reducing factors (Boote *et al*., 1996; Affholder *et al*., 2013; Schulthess *et al*., 2013) -or process-based crop growth simulation models (Farre *et al*., 2002; Abbas *et al*., 2017; Tariq *et al*., 2018). When using crop simulation models, they must first be calibrated and evaluated for an extensive range of environments (Robertson and Lilley, 2016). The major strength of the modeling approach is that they can integrate seasonal climate variability over several years with crop management to determine the magnitude and inconsistency of the attainable grain yield.

Crop simulation models have been extensively used to extrapolate results from field-specific research to larger areas (Bouman and van Laar, 2006; Probert *et al*., 1995; Abbas *et al*., 2017; Tariq *et al*., 2018) and have been applied to crop productivity analysis (Mourice *et al*., 2014) and yield-gap analysis (Bhatia *et al*., 2008; Bindraban *et al*., 2000; Lobell *et al*., 2009; van Ittersum *et al*., 2013; Poulton *et al*., 2015; Zu *et al*., 2018; Dias and Sentelhas, 2018). Crop models within the Decision Support System for Agrotechnology Transfer (DSSAT; Jones *et al*., 2003; Hoogenboom *et al*., 2019a, b) are widely used for different environmental conditions and management practices (Jones *et al*., 2003; Timsina and Humphreys, 2006; Ahmad *et al*., 2015; Abbas *et al*., 2017; Tariq *et al*., 2018). The primary objective of crop simulation models is to determine crop productivity, resource management, and environmental effect as a function of crop management practices, soil physiochemical characteristics and local weather conditions (Hoogenboom *et al*., 2019a, b; Tsuji *et al*., 1998). This ability of crop models may be used in conjunction with on-station trials, and farm surveys, to help advance our understanding of the yield-gap between current and attainable crop yield.

The low canola yield in Pakistan is associated with management practices such as sowing time, plant density, fertilizer, and irrigation (Qian *et al*., 2018). Proper N and irrigation water management are both essential practices for maximum grain and oil yield of canola. Nitrogen affects canola growth and development (Ozer, 2003) and grain and oil yield (Rathke and Schuster, 2001). Fertilization strategies such as split applications of N fertilizer have resulted in an increase in canola grain yield and quality (Faramarzi *et al*., 2009; Jing *et al*., 2016) and a reduction of N losses via leaching, denitrification, runoff/erosion, and volatilization (Grant *et al*., 2012; Fatima *et al*., 2018). Previous studies have shown that canola grain yield increases when N is split into two side-dress applications (1/2 at sowing and 1/2 at first irrigation) (Tamagno *et al*., 1999) or 50-70% of N applied as a basal dose and a top dressing (Ali and Ullah, 1995).

Best irrigation management practices are also helpful in increasing canola grain yield. Johnston *et al*. (2002) found that drought stress at anthesis largely influences the canola yield components. Supplemental irrigation at the flowering and grain-filling stage can increase canola grain and oil yields (Dogan *et al*., 2011). If irrigation water is limited, a single application of water at flowering stage should minimize the risk of yield losses due to water stress (Istanbulluoglu *et al*., 2010). If farmers rely only on conventional water management practices, there is a need for a participatory approach for the adoption of improved farming practices in the common canola growing regions of Pakistan.

Until now, the CROPGRO-Canola model of DSSAT has not been used for exploring the yield-gap of canola for conditions in water limiting regions such as Punjab, Pakistan or elsewhere. The goal of this study was, therefore, to integrate on-station trials and survey data with modeling to identify the limiting factors of current management practice and to quantify the yield-gap of irrigated canola in a water limiting environment. The specific objectives were to evaluate the ability of the CSM-CROPGRO-Canola model to a) simulate on-station trial results, b) to simulate farm survey data from four districts in southern Punjab, Pakistan, and c) to identify limitations on production technology and develop strategies for the bridging yield-gap.

**Materials and methods**

Four field experiments with canola were grown in the research unit of Bahauddin Zakariya University Multan Pakistan to determine the yield-gap between attainable and farmers’ yield. Soil samples were obtained in each trial prior to sowing. Sowing dates, cultivars, N levels, and N application treatments were applied in each experiment separately. Grain and biomass yield data were obtained from each experiment. Meanwhile, farmers’ field survey data were also collected. The CSM-CROPGRO-Canola model was used to simulate canola yield and support the yield-gap analysis.

*Experimental site*

Field experiments were conducted during the winter seasons of 2015-2016 and 2016-2017 at Bahauddin Zakariya University (BZU), Multan, Punjab, Pakistan (30.19° latitude N, 71.46° longitude E and 125 m above the sea level). The soil of the experimental site belongs to “*Sindhlianwali”* soil series(fine silty, mixed, hyperthermic, sodic haplocambids) (Ahmad *et al*., 2014). Soil measurements for physical and chemical properties were obtained prior to sowing of canola in both years.

*Experimental procedure*

The canola experiments (Table S1) were sown following a randomized complete block design. The experimental field was irrigated eight days before seed-bed preparation and then ploughed three times, followed by planking. Canola was hand drilled in rows at a spacing of 45 cm and around 15 cm between plants. Weeds were controlled manually and mechanically. Irrigation water was provided via tube wells. All other management practices were implemented in accordance with the instructions of the local agriculture department and consistent across all trials and years.

*Plant sampling and measurements*

Growth and development data were obtained weekly following the methodology described by Deligios *et al*. (2013) and Jing *et al*. (2016). Development stages were recorded when half of the plants from each experimental unit reached a given stage. Plants in a 1 m2 quadrat were collected at 25-day intervals from each plot for growth final biomass and yield and yield components. Samples were oven-dried for 72 hours at 65 °C for dry weight. A leaf area meter (model LI-3100; LICOR Inc., Nebraska, USA) was used to obtain leaf area. Canola was hand-harvested with the help of a sickle in all experiments during the third week of March in 2016 and 2017 to obtain for final yield and yield components. The samples were then dried for five days and manually threshed.

*On-farm Survey Data*

A survey, prepared following the procedure from Fermont *et al*. (2009), was used to obtain information from 100 growers across four districts (Multan, Khanewal, Vehari, and Bahawalpur) (Fig. 1) in Punjab, Pakistan during the 2016-2017 growing season. We recorded on-farm canola yield along with management practices including the seeding rate, sowing time, sowing method, canola cultivar, N fertilizer strategy, and irrigation strategy. The CROPGRO-Canola model was then used to simulate canola grain yield from each of the 100 farmer fields surveyed using traditional farming practices.

*CSM-CROPGRO-Canola model description*

The CSM-CROPGRO-Canola model (Deligios *et al*., 2013; Jing *et al*., 2016) of the Decision Support System for Agro-technology Transfer (DSSAT v4.7.5; Hoogenboom *et al*., 2019a, b), was used in this study. The model simulates the growth and development of canola based on carbon, water, N, and energy balance principles. The model requires information on crop management practices, soil characteristics, genetic coefficients and weather parameters for the simulation of daily growth and development and final yield prediction.

The model was calibrated with results from a nitrogen rates study conducted during the 2015-2016 growing season for the cultivar Faisal at a rate of 150 kg N/ha. A trial-and-error procedure was used for calibration by comparing the model predicted data with the field experimental observed data (Table S2) and the process generated Genetic coefficients for canola cultivars (Table S3).

The performance of the model was evaluated with the N rate treatments that were not used for calibration and three other field experiments that included irrigation regimes, N strategies and sowing dates as treatments.

*Weather conditions*

The climate of the region is of continental type with hot and dry summers and cold and dry winters (Ahmad *et al*., 2015; Tariq *et al*., 2018). During the 2015-2016 and 2016-2017 growing seasons, weather conditions were characterized by daily maximum and minimum temperatures that ranged from 8ºC to 37ºC and 2ºC to 27ºC, total solar radiation that ranged from 4.6 to 21.6 MJ/m2/d, and total seasonal rainfall that ranged from 45 to 56 mm (Fig. 2).

*Simulation scenarios for yield-gap analysis*

Long-term simulations of canola yield were conducted for conditions for all the 100 farms that were surveyed using historical weather data. The simulation scenarios of included potential yield (YP, without water and N limitations), achievable yield (YA, recommended/approved management practices), water-limited yield (YWL, limited water conditions), N-limited (YNL, N-limited conditions), water and N-limited yield (YWNL, both water and N limited conditions), and overall farmer field (YOFF, observed yield at a farm). Observed canola yield from 1980 to 2016, collected for selected districts from the Department of Agriculture (Extension Wing), Government of the Punjab, Pakistan were also used. Management practices other than water and N were kept the same across the simulations. We defined the yield-gap (YG) as follows:

$YG\_{i} = Y\_{j} - Y\_{k}$ (1)

where i correspond to yield gap under conditions of WL, NL, WNL, and OFF; j = YP, YA; and k = YWL, YNL, YWNL, and YOFF. The YG was then expressed as percent loss of the potential and achievable yields, as follows:

$YG\_{i} = \frac{Y\_{j} - Y\_{k}}{Y\_{j}}$ (2)

The percentages indicating how close YWL, YNL, YWNL, and YOFF are from the simulated YP and achievable yield YA (Zu *et al*., 2018).

*Statistical analysis*

The results from the field experiments were subjected to analysis of variance techniques using STATISTICS 8.1. Treatment means were subjected to post-hoc comparisons using the least significant difference test (Steel *et al*., 1997) at alpha = 0.05. The farm survey data were analyzed using linear regression and probability of exceeding. The performance of the CSM-CROPGRO-Canola model was evaluated using the root mean square error (RMSE) and normalized RMSE (RMSEn) (Wallach and Goffinet, 1987) and the Wilmott (Wilmott, 1981) index of agreement (d-index):

$RMSE =\left[\sqrt{\frac{\sum\_{i=1}^{n}\left(Si-Oi\right)^{2}}{N}}\right]$ (3)

$RMSE\_{n}= \left[\frac{RMSE x 100}{\overline{O}}\right]$ (4)

$d-index = 1 - \left[\frac{\sum\_{i=1}^{n}\left(Si - Oi\right)^{2}}{\sum\_{i=1}^{n}(\left|S^{'}i\right|+\left|O^{'}i\right|)^{2}}\right]$ (5)

where ‘Si’ and ‘*Oi*’ are simulated and observed values ‘*N*’ is the sample size, $\overbar{O}$ is the average for the observed values, $S'\_{i}=\left(S\_{i}-\overbar{O}\right)$ and $O'\_{i}=\left(O\_{i}-\overbar{O}\right)$. The lower values of RMSE represent a better fit. The RMSEn provides a comparative change of simulated versus observed data expressed in percentage. Simulations were considered excellent, good, fair, and poor when RMSEn is < 10%, > 10 and < 20%, >20% and < 30%, and > 30%, respectively (Loague and Green, 1991). According to Willmott (1981), a value of 1 indicates a perfect match while a value of 0 indicates no agreement.

**Results**

*Model calibration*

Research trials were conducted under well-management practices for all treatments throughout the 2015-2016 and 2016-2017 growing seasons. The genetic coefficients for canola cultivars were determined by trial and error. The model was calibrated using experimental data from a trial conducted during the 2015-2016 growing season on the canola cultivar Faisal with results from the 150 kg N/ha treatment. Simulated phenology showed a good agreement with the observed results. The difference in the simulated days to anthesis, first pod, first seed and physiological maturity compared to the observed data was 1, 1, 0, and 0, respectively (Table 1). The simulated maximum leaf area index (LAI) was in good agreement with the observed results as well; simulated LAI ranged from 2.23 to 2.49 m2/m2 while observed LAI ranged from 2.18 to 2.47 m2/m2. The RMSE and the d-index of agreement were 0.39 and 0.93, respectively (Fig. 3(a-l)). The simulated and observed above-ground biomass ranged from 7709 to 13285 kg/ha and 6538 to 12919 kg/ha, respectively. The RMSE and d-index of agreement were 1384 kg/ha and 0.99, respectively (Fig. 3(a-l)). The simulated and observed grain yield also showed good agreement, with RMSE of 113 and *d*-index of agreement of 0.92 (Table S4).

*Model evaluation*

The performance of the canola model was assessed against results from field experiments and farmers’ surveys. The canola model simulations were in agreement with observed results from the field experiments and the survey data. Simulated phenology was in good agreement with observed results for all four trials for both years (Table S5). Across experiments and years, RMSE and *d*-index of agreement, varied from 0.31 to 0.53 and 0.90 to 0.97 for LAI; from 436 to 1683 and 0.95 to 0.99 for aboveground biomass, and 60 to 194 and 0.92 to 0.98 for grain yield. The simulation results for conditions for the 100-farmer fields showed a RMSE of 202, a *d*-index of 0.88, and a R2, of 0.63. Simulated grain yield ranged from 845 to 2804 kg/ha, while, observed grain yield ranged from 783 to 2782 kg/ha across N rates experiment (Fig. 3). For irrigation experiment simulated yield ranged from 783 to 2865 kg/ha, observed yield ranged from 695 to 2648 kg/ha (Fig. 4). Simulated yield for N application strategies ranged from 2281 to 2785 kg/ha, however, observed yield ranged from 2281 to 2736 kg/ha (Fig. 5). For sowing dates experiment simulated yield ranged from 2250 to 2858 kg/ha and observed yield ranges from 2139 to 2791 kg/ha (Fig. 6). The grain yield of canola from the survey varied from slighlty under 1000 kg/ha to slightly above 2500 kg/ha. On average, 19:50, 2:5, and 11:50 of farmer yields from the survey data were between 1000 to 1650, 1651 to 1945, and 1946 to 2500 kg/ha. Overall, the model effectively simulated high yields but tended to overestimate the low yields (Fig. 7).

*Yield-gap analysis of canola*

After calibration and evaluation, the CSM-CROPGRO-Canola model was used to simulate scenarios for YP and YA using the seasonal analysis tool of DSSAT (Thornton and Hoogenboom, 1994; Thornton *et al*., 1995, 1998). Average simulated grain yield for YP was 3056 kg/ha and for YA was 2310 kg/ha that which already accounted for a yield-gap of 746 kg/ha, equivalent to over 6:25 proportion (Table 2). The mean observed canola grain yield grown under various scenarios like nitrogen limited was 1530 kg/ha, water limited 1658 kg/ha, nitrogen and water limited 1169 kg/ha, and on farmer field was 867 kg/ha. The average yield-gap between potential yield with nitrogen limited was 1525 (1:2), water limited 1398 (23:50), nitrogen and water limited 1887 (31:50), and on farmer field 2189 (18:25). Similarly, the average yield-gap between achieved yield and nitrogen limited 780 (17:50), water limited 652 (7:25), nitrogen and water limited 1141 (7:50), and on farmer field 1443 (31:50).

**Discussion**

Both the on-station research and survey results show the need to improve crop management practices to reduce the current yield-gap in canola production in Punjab, Pakistan. However, the yield-gap analysis encompasses complexities that require the use of crop modeling to complement the results obtained from on-station and on-station research. We, therefore, used the CROPGRO-Canola model of DSSAT to tackle the problems facing local farmers in making decisions specifically linked to irrigation, fertilizer, sowing date, and cultivars with a superior genetic potential. This study showed that the main causes for a low yield are associated with inefficiencies in crop management practices. Such a reality has a cascading effect resulting in a very large yield gap. For example, the use of low-quality seed with little attention to other management practices such as sowing dates, fertilization strategy, and irrigation management is a recipe for failure. In other words, failing to adopt improved agronomic practices was the principal reasons for marginally lower canola grain yield than the research trial grain yields. In fact, sowing high-yielding canola cultivars under improved agronomic practices could translate into an attainable yield of ≈ 2500 kg/ha.

The results showed that canola yield from surveyed farmers’ fields were lower than the maximum achievable yield. This poor performance evidenced, once more, that less than optimum management practices are the main cause for the low actual yield. Often, farmers do not follow the recommendations of best management practices obtained from research because of the lack of proper extension programs to reach a mostly non-educated population who have an urgent need for basic information. For example, farmers tend to sow canola in early November to mid-December, which is too late compared to the recommended optimum sowing date that ranges from 20 September to 31 October in Punjab, Pakistan. The consequence of this is a low canola germination resulting ultimately in a low grain yield. Similarly, most farmers apply a sub-optimal amount of fertilizer-N and practice a single application at sowing, resulting in N loss through leaching, denitrification, runoff, and volatilization (Faramarzi *et al*., 2009; Ahmad *et al*., 2012, 2016a, b; Fatima *et al*., 2018). In a region where water is one of the most important inputs that affects crops growth, proper irrigation management is strategically critical. The farmers inability to properly supply water at critical periods of canola growth results in an avoidable reduction in yield. This study showed that proper irrigation alone can increase the expected grain yield for each canola variety (Table S3). Farmers’ management practices in the region shows that their maximum expected yield corresponds to 2/3 of the minimum and less than half of the maximum achievable yield (Table 1). As discussed earlier, corrective measures exist, but there seems to be a disconnect between the research findings, extension to small-holder farmers, and the adoption of appropriate management practices.

In this study we used a combination of field experiments, a survey of on-farm practices and yield, and modeling to advance our understanding on factors driving low yield of canola in southern Punjab, Pakistan. The canola model successfully simulated growth and yield of canola for both farmer and best management practices scenarios. The yield-gap analysis revealed inefficiencies related to basic management practices, including poor quality seed, sowing dates, fertilization strategy, and irrigation water management as the main causes for a low canola yield. There was a difference between simulated and observed results, but in general the model performed satisfactorily although spatial variability is well-known to be associated with differences in management practices (van Ittersum *et al*., 2013; Yanga *et al*., 2014; Poulton *et al*., 2015; Ahmad *et al*., 2017a, b). In general, the simulated yield for various canola management practices correlated well with the average observed farmers’ yield but for some instances the observed yield was not adequately simulated. This might be due to the high variation on farmer practices like sowing time. Overall, the results from this study contributed to the revision of potential and achievable yield of canola. The simulated yield was found to be within the results from research on best management practices.

**Conclusions**

The CSM-CROPGRO-Canola model satisfactorily simulated growth, development, and yield of canola under scenarios of potential, achievable, N-, water-, N –and -water limited and overall farmer field conditions in southern Punjab, Pakistan. A large gap between simulated potential, achievable and on-station yields for canola showed a high potential to increase canola productivity in the study region. The yield-gap resulting from drought stress was less compared to N stress, probably due to canola being grown in a region with limited water and, thus, the need for irrigation. Finally, the canola yield-gap can be overcome through management practices including the selection of the best cultivar and sowing date and an appropriate N fertilizer strategy. This research showed that applied research can play an important role in bridging the gap in canola yield in southern Punjab, Pakistan. This, however, will need an aggressive outreach program including government support policies aiming at adapting extension strategies to reach canola producers.

**Author Contributions**

SA, SH, MA, and MAG conceived and designed the study. GA and ZF conducted data gathering. MAR performed statistical analyses. AG and CJW read the first and second drafts. GH overall supervised the study. All the authors read the manuscript before submission.

**Declaration of Interest**

The authors declare that they have no conflict of interest.

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**Ethical Standards**

Not applicable

**References**

**Abbas G, Ahmad S, Ahmad A, Nasim W, Fatima Z, Hussain S, Habib ur Rehman M, Khan MA, Hasanuzzaman M, Fahad S, Boote KJ and Hoogenboom G** (2017) Quantification the impacts of climate change and crop management on phenology of maize-based cropping system in Punjab, Pakistan. *Agriculture and Forest Meteorology* 247, 42–55.

**Affholder F, Poeydebat C, Corbeels M, Scopel E and Tittonell P** (2013) The yield gap of major food crops in family agriculture in the tropics: Assessment and analysis through field surveys and modelling. *Field Crops Research* 143, 106–118.

**Ahmad A, Ashfaq M, Rasul G, Wajid SA, Khaliq T, Rasul F, Saeed U, Habib ur Rahman M, Hussain J, Baig IA, Naqvi SAA, Bokhari SAA, Ahmad S, Naseem W and Hoogenboom G** (2015) Impact of climate change on the rice-wheat cropping system of Pakistan. In: *Handbook of Climate Change and Agro-ecosystems*, Vol. 3 (editors) Hillel, D., and Rosenzweig, C. Imperial College Press and the American Society of Agronomy.

**Ahmad S, Ali H, Ismail M, Shahzad MI, Nadeem M, Anjum MA, Zia-Ul-Haq M, Firdous N, Khan MA** (2012) Radiation and nitrogen use efficiencies of C3 winter cereals to nitrogen split application. *Pakistan Journal of Botany* 44, 139–149.

**Ahmad S, Abbas G, Fatima Z, Khan RJ, Anjum MA, Ahmed M, Khan MA, Porter CH and Hoogenboom G** (2017b) Quantification of the impacts of climate warming and crop management on canola phenology in Punjab, Pakistan. *Journal of Agronomy and Crop Science* 203, 442–452.

**Ahmad S, Abbas Q, Abbas G, Fatima Z, Atique-ur-Rehman, Naz S, Younis H, Khan RJ, Nasim W, Habib ur Rehman M, Ahmad A, Rasul G, Khan MA and Hasanuzzaman M** (2017a) Quantification of climate warming and crop management impacts on cotton phenology. *Plants* 6, 1–16.

**Ahmad S, Ali H, Farooq U, Khan SU, Atique-ur-Rehman, Sarwar N, Shahzad AN, Dogan H, Hussain S, Sultan MT, Waheed A, Zia-ul-Haq M, Hussain K and Khan MA** (2016a) Improving nitrogen and radiation-use-efficiencies of C4 summer cereals by split nitrogen applications under irrigated arid environment. *Turkish Journal of Agriculture and Forestry* 40, 280–289.

**Ahmad S, Nadeem M, Abbas G, Fatima Z, Khan RJZ, Ahmed M, Ahmad A, Rasul G and Khan MA** (2016b) Quantification of the effects of climate warming and crop management on sugarcane phenology. *Climate Research* 71, 47–61.

**Ahmad S, Raza I, Ali H, Shahzad AN, Atiq-ur-Rehman, Sarwar N** (2014) Response of cotton crop to exogenous application of glycinebetaine under sufficient and scarce water conditions. *Brazilian Journal of Botany* 37, 407–415.

**Ali MH and Ullah MJ** (1995) Effect of different levels and timing of nitrogen application on growth and yield of rapeseed. *Annals of Bangladesh Agriculture* 5, 115–120.

**Anderson W, Johansen C and Siddique KHM** (2016) Addressing the yield gap in rainfed crops: a review.‎ *Agronomy for Sustainable Development* 36, 18.

**Bhatia VS, Singh P, Wani SP, Chauhan GS, Kesava Rao AVR, Mishra AK and Srinivas K** (2008) Analysis of potential yields and yield gaps of rainfed soybean in India using CROPGRO-Soybean model. *Agricultural and Forest Meteorology* 148, 1252–1265.

**Bindraban PS, Stoorvogel JJ, Jansen DM, Vlaming J, Groot JJR** (2000) Land quality indicators for sustainable land management: proposed method for yield gap and soil nutrient balance. *Agriculture, Ecosystem and Environment* 81, 103–112.

**Boote KJ, Jones JW and Pickering NB** (1996) Potential uses and limitations of crop models. *Agronomy Journal* 88, 704–716.

**Boote KJ, Mínguez MI and Sau F** (2002) Adapting the CROPGRO legume model to simulate growth of faba bean. *Agronomy Journal* 94, 743–756.

**Bouman BAM and van Laar HH** (2006) Description, evaluation of the rice growth model ORYZA 2000 under nitrogen-limited conditions. *Agricultural Systems* 87, 249–273.

**Dias HB and Sentelhas PC** (2018) Sugarcane yield gap analysis in Brazil – a multi-model approach for determining magnitudes and causes. *Science of Total Environment* 637–638, 1127–1136.

**Deligios PA, Farci R, Sulas L, Hoogenboom G, and Ledda L** (2013) Predicting growth and yield of winter rapeseed in a Mediterranean environment: Model adaptation at a field scale. *Field Crops Research* 144, 100–112.

**Dogan E, Copur O, Kahraman A, Kirnak H and Guldur ME** (2011) Supplemental irrigation effect on canola yield components under semiarid climatic conditions. [*Agricultural Water Management* 98, 1403–140](file:///C%3A%5Cpapers%5Cirrigation%5Cdx.doi.org%5C10.1016%5Cj.agwat.2011.04.006)8.

**Faramarzi A, Barzegar A, Zolleh HH, Mohammadi H, Ardakani MR and Normohammadi G** (2009) Response of canola (*Brassica napus* cultivars to rate and split application of nitrogen fertilizer. *Australian Journal of Basic and Applied Sciences* 3, 2030–2037.

**Faramarzi M, Abbaspour KC, Schulin R and Yang H** (2009) Modelling blue and green water resources availability in Iran. *Hydrological Processes* 23, 486–501.

**Farre I, Robertson MJ, Walton GH and Asseng S** (2002) Simulating phenology and yield response of canola to sowing date in Western Australia using the APSIM model. *Australian Journal of Agricultural Research* 53, 1155–1164.

**Fatima Z, Abbas Q, Khan A, Hussain S, Ali MA, Abbas G, Younis H, Naz S, Ismail M, Shahzad MI, Nadeem M, Farooq U, Khan SU, Javed K, Khan AA, Ahmed M, Khan MA and Ahmad S** (2018) Resource use efficiencies of C3 and C4 cereals under split nitrogen regimes. Agronomy 8(5), 69.

**Fermont AM, van Asten PJA, Tittonell P, van Wijk MT and Giller KE** (2009) Closing the cassava yield gap: an analysis from smallholder farms in East Africa. *Field Crops Research* 112, 24–36.

**Government of Pakistan** (2018) Economic Survey of Pakistan, 2017–18, Economic Advisory Wing, Finance Division, Govt. of Pakistan, Islamabad, pp. 13–32.

**Grant CA, Wu R, Selles F, Harker KN, Clayton GW, Bittman S, Zebarth BJ and Lupwayi NZ** (2012) Crop yield and nitrogen concentration with controlled release urea and split application of nitrogen as compared to non-coated urea applied at seeding. *Field Crops Research* 127, 170–180.

**Hoogenboom G, Porter CH, Boote KJ, Shelia V, Wilkens PW, Singh U, White JW, Asseng S, Lizaso JI, Moreno LP, Pavan W, Ogoshi R, Hunt LA, Tsuji GY and Jones JW** (2019a) The DSSAT crop modeling ecosystem. *In*: p.173-216 [Boote KJ (editor)] Advances in Crop Modeling for a Sustainable Agriculture. Burleigh Dodds Science Publishing, Cambridge, United Kingdom (<http://dx.doi.org/10.19103/AS.2019.0061.10>)

**Hoogenboom G, Porter CH, Shelia V, Boote KJ, Singh U, White JW, Hunt LA, Ogoshi R, Lizaso JI, Koo J, Asseng S, Singels A, Moreno LP, and Jones JW** (2019b) Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.7.5 (https://DSSAT.net). DSSAT Foundation, Gainesville, Florida, USA.

**Istanbulluoglu A, Arslan B, Gocmen E, Gezer E and Pasa C** (2010) Effects of deficit irrigation regimes on the yield and growth of oilseed rape (*Brassica napus*L.). *Biosystems Engineering* 105, 388–394.

**Jing Q, Shang J, Qian B, Hoogenboom G, Huffman T, Liu J, Ma B, Geng X, Jiao X, Kovacs J and Walters D** (2016) Evaluation of the CSM-CROPGRO-Canola model for simulating canola growth and yield at west Nipissing in Eastern Canada. *Agronomy Journal* 108, 1–10.

**Johnston AM, Tanaka DL, Miller PR, Brandt SA, Nielsen DC, Lafond GP and Rieveland NR** (2002) Oilseed crops for semiarid cropping systems in the Northern Great Plains. *Agronomy Journal* 94, 231–241.

**Jones JW, Hoogenboom G, Porter CH, Boote KJ, Batchelor WD, Hunt LA, Wilkens PW, Singh U, Gijsman AJ and Ritchie JT** (2003) DSSAT Cropping System Model. *European Journal of Agronomy* 18, 235–265.

**Loague K and Green RE** (1991) Statistical and graphical methods for evaluating solute transport models: Overview and application. *Journal of Contaminant Hydrology* 7, 51–73.

**Lobell DB, Cassman KG, Field CB** (2009) Crop yield gaps: their importance, magnitudes, and causes. *Annual Review of Environmental Resources* 34, 179–204.

**Mahmood T, Ejaz-ul-Hasan, Ali M and Hussain M** (2012) Faisal canola: a new high yielding canola variety for general cultivation in Punjab. *Journal of Agricultural Research* 50, 321–328.

**Mourice SK, Rweyemamu CL, Tumbo SD and Amuri N** (2014) Maize cultivars specific parameters for decision support system for agrotechnology transfer (DSSAT) application in Tanzania. *American Journal of Plant Sciences* 5, 821–833.

**Noreen S, Noor S, Ahmad S, Bibi F and Hasanuzzaman M** (2016) Quantifying some physiological and productivity indices of canola (*Brassica napus* L.) crop under an arid environment. Not. Bot. Horti. Agrobo. 44, 272–279.

**Oteng-Dark P, Yeboah S, Addy SNT, Amponsah S and Danquah EO** (2013) Crop modeling: A tool for agricultural research – A review. *E3 Journal of Agricultural Research and Development* 2, 1–6.

**Ozer H** (2003) Sowing date and nitrogen rate effects on growth, yield and yield components of two summer rapeseed cultivars. *European Journal of Agronomy* 19, 453–463.

**Poulton PL, Vesna T, Dalgliesh NP and Seng V** (2015) Applying simulation to improve rice varieties in reducing the on-farm yield gap in Cambodian lowland rice ecosystems. *Experimental Agriculture* 51, 264–284.

**Probert ME, Keating BA, Thompson JP and Parton WJ** (1995) Modelling water, nitrogen, and crop yield for a long-term fallow management experiment. *Australian Journal of Experimental Agriculture* 35, 941–950.

**Qian B, Jing Q, Bélanger G, Shang J, Huffman T, Liu J and Hoogenboom G** (2018) Simulated canola yield responses to climate change and adaptation in Canada. *Agronomy Journal* 110, 133-146.

**Rathke GW and Schuster C** (2001) Yield and quality of winter oilseed rape related to nitrogen supply. In: Horst, W.J., *et al*. (Eds.), Plant Nutrition: Food Security and Sustainability of Agro-Ecosystems through Basic and Applied Research. Kluwer Academic Publishers, Dordrecht, pp. 798–799.

**Robertson MJ and Lilley JM** (2016) Simulation of growth, development and yield of canola (*Brassica napus*) in APSIM. *Crop and Pasture Science* 67, 332–344.

**Robertson M, Kirkegaard J, Peake A, Creelman Z, Bell L, Lilley J, Midwood J, Zhang H, Kleven S, Duff C, Lawes R and Riffkin P** (2016) Trends in grain production and yield gaps in the high-rainfall zone of southern Australia. *Crop and Pasture Science* 67, 921–937.

**Steel RGD, Torrie JH and Dickey DA** (1997) Principles and Procedures of Statistics: A Biometrical Approach. 3rd Ed. New York, NY, USA: McGraw-Hill.

**Schulthess U, Timsina J, Herrera JM and McDonald A** (2013) Mapping field-scale yield gaps for maize: An example from Bangladesh. *Field Crops Research* 143, 151–156.

**Tamagno LN, Chamorro AM and Sarandon SJ** (1999) Split nitrogen application on rapeseed; effects on seed yield and seed quality. *Revista de la Facultad de Agronomical La Plata* 104, 25–34.

**Tariq M, Ahmad S, Fahad S, Abbas G, Hussain S, Fatima Z, Nasim W, Mubeen M, Habib ur Rehman M, Khan MA, Adnan M, Wilkerson CJ and Hoogenboom G** (2018) The impact of climate warming and crop management on phenology of sunflower-based cropping systems in Punjab, Pakistan. *Agricultural and Forest Meteorology* 256–257, 270–282.

**Thornton PK, and Hoogenboom G** (1994) A computer program to analyze single-season crop model outputs. *Agronomy Journal* 86, 860–868.

**Thornton PK, Hoogenboom G, Wilkens PW, and Bowen WT** (1995) A computer program to analyze multiple-season crop model outputs. *Agronomy Journal* 87, 131–136.

**Thornton P K, Hoogenboom G, Wilkens PW, and Jones JW** (1998) Seasonal analysis. In G. Y. Tsuji, G. Uehara, & S. Balas (Eds.), DSSAT version 3, vol. 3–2 (pp. 1–65). Honolulu: University of Hawaii.

**Timsina J and Humphreys E** (2006) Performance of CERES-rice and CERES-wheat models in rice–wheat systems: a review. *Agricultural Systems* 90, 5–31.

**Tsuji GY, Hoogenboom G, and Thornton PK** (1998) Understanding options for agricultural production. Systems approaches for sustainable agricultural development. Dordrecht: Kluwer Academic.

**Uehara G and Tsuji GY** (1998) Overview of IBSNAT. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, London and International Consortium for Agricultural Systems Applications, pp. 1–7.

**van Ittersum MK, Cassman KG, Grassini P, Wolf J, Tittonell P and Hochman Z** (2013) Yield gap analysis with local to global relevance – a review. *Field Crops Research*143, 4–17.

**Wallach D and Goffinet B** (1987) Mean squared error of prediction in models for studying ecological and agronomic systems. *Biometrics* 43, 561–573.

**Willmott CJ** (1981) On the validation of models. *Physical Geography* 2, 184–194.

**Yanga JM, Yangb JY, Liub S and Hoogenboom G** (2014) An evaluation of the statistical methods for testing the performance of crop models with observed data. *Agricultural Systems* 127, 81–89.

**Zu Q, Mi C, Liu DL, He L, Kuang Z, Fang Q, Ramp D, Li L, Wang B, Chen Y, Li J, Jin N and Yu Q** (2018) Spatio-temporal distribution of sugarcane potential yields and yield gaps in Southern China. *European Journal of Agronomy* 92, 72–83.

**Table 1.** Observed (O) and simulated (S) phenology, root mean square error and d-index of agreement for growth from model calibration and evaluation during the 2015-2016 and 2016-2017 growing seasons

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Crop characteristics**†** | Nitrogen Rates |  | Irrigation Regimes |  | Nitrogen Strategy |  | Sowing dates |
| O | S |  | O | S |  | O | S |  | O | S |
| **2015-2016** |
| *Phenology* |  |  |  |  |  |  |  |  |  |  |  |
| Anthesis date | 53 | 52 |  | 52 | 53 |  | 52 | 53 |  | 54 | 55 |
| First pod date | 70 | 71 |  | 70 | 71 |  | 70 | 71 |  | 74 | 75 |
| First seed date | 108 | 108 |  | 107 | 107 |  | 106 | 107 |  | 106 | 107 |
| Maturity date | 159 | 158 |  | 159 | 159 |  | 159 | 159 |  | 159 | 160 |
| *Growth* | *d-stat* | *RMSE* |  |  *d-stat* | *RMSE*  |  |  *d-stat* | *RMSE*  |  |  *d-stat* | *RMSE*  |
| LAI | 0.96 | 0.052 |  | 0.95 | 0.101 |  | 0.70 | 0.101 |  | 0.98 | 0.35 |
| Biomass | 0.96 | 247 |  | 0.97 | 740 |  | 0.79 | 298 |  | 0.99 | 249 |
| **2016-2017** |
| *Phenology* |  |  |  |  |  |  |  |  |  |  |  |
| Anthesis date | 52 | 51 |  | 50 | 51 |  | 50 | 51 |  | 52 | 53 |
| First pod date | 69 | 68 |  | 69 | 70 |  | 69 | 69 |  | 72 | 73 |
| First seed date | 104 | 105 |  | 105 | 106 |  | 104 | 105 |  | 105 | 106 |
| Maturity date | 158 | 159 |  | 156 | 156 |  | 159 | 160 |  | 157 | 158 |
| *Growth* | *d-stat* | *RMSE* |  |  *d-stat* | *RMSE*  |  |  *d-stat* | *RMSE*  |  |  *d-stat* | *RMSE*  |
| LAI | 0.93 | 0.053 |  | 0.96 | 0.156 |  | 0.74 | 0.127 |  | 0.97 | 0.42 |
| Biomass | 0.95 | 436 |  | 0.98 | 825 |  | 0.76 | 345 |  | 0.98 | 292 |

† d to a given stage of development, LAI = leaf area index (m2/m2) and Biomass corresponds to aboveground biomass (kg/ha)

**Table 2.** The minimum, maximum, and mean values of long-term (1980-2016) average of simulated potential (YP), achievable (YA), observed N-limited (YNL), water-limited (YWL), N and water limited (YNWL), and overall farmers field (YOFF) yield

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Item** | **YP** | **YA** | **YNL** | **YWL** | **YNWL** | **YOFF** |
| **(kg/ha)** |
| Minimum | 2622 | 1852 | 1099 | 1275 | 765 | 522 |
| Maximum | 3497 | 2725 | 1792 | 1874 | 1464 | 1218 |
| Average | 3056 | 2310 | 1530 | 1658 | 1169 | 867 |
| St. Deviation | 274 | 233 | 199 | 146 | 207 | 221 |

**Fig. 1.** The selected locations for the simulation of potential and achievable yield of canola and the major causes for the yield cap, i.e., water limited, nitrogen limited, water and nitrogen limited and other crop management practices, for four districts in southern Punjab, Pakistan. The circles indicate locations of field experiments used for CSM-CROPGRO-Canola model calibration and evaluation

**Fig. 2.** Daily maximum and minimum temperatures (a, c), solar radiation and precipitation (b, d) for canola growing seasons 2015-2016 (a, b; unfilled symbols) and 2016-17 (c, d; filled symbols) in Multan, Pakistan

**Fig. 3.** Simulated LAI (dotted lines) and observed LAI (triangular filled and unfilled symbols) and simulated biomass (continuous lines) and observed biomass (round unfilled and filled symbols) of canola at variable nitrogen application rates (Model calibration and evaluation data) during 2015-2016 (a, b, c, d, e, and f) and 2016-2017 (g, h, i, j, k, and l) at the study site

**Fig. 4.** Simulated LAI (dotted lines) and observed LAI (downward triangular unfilled and filled symbols) and simulated biomass (continuous lines) and observed biomass (round filled and unfilled symbols) of canola at variable irrigation regimes (Model evaluation data) during the 2015-2016 (a, b, c, and d) and 2016-2017 (e, f, g, and h) growing seasons at the study site

**Fig. 5.** Simulated LAI (dotted lines) and observed LAI (star filled and unfilled symbols) and simulated biomass (continuous lines) and observed biomass (square unfilled and filled symbols) of canola at variable nitrogen application strategy (Model evaluation data) during 2015-2016 (a, b, c, and d) and 2016-2017 (e, f, g, and h) at the study site

**Fig. 6.** Simulated LAI (dotted lines) and observed LAI (star unfilled and filled symbols) and simulated biomass (continuous lines) and observed biomass (square filled and unfilled symbols) of canola at variable sowing dates (Model evaluation data) during year 2015-2016 (a, b, and c) and 2016-2017 (d, e, and f) at the study site

**Fig. 7.** Relationship between simulated and observed 100 farm canola yield (a) using CSM-CROPGRO-Canola model and probability of exceeding (b) in all four strata of canola crop in southern Punjab, Pakistan during 2016-2017 (Model evaluation at farmer field data)

**Fig. 8.** Farmer-Scientist determined yield-gap at farmer fields in southern Punjab, Pakistan



**Fig. 1.**

**Fig. 2.**

**N / ha**

**N / ha**

**N / ha**

**N / ha**

**N / ha**

**N / ha**

**N / ha**

**N / ha**

**N / ha**

**N / ha**

**N / ha**

**N / ha**

**LAI (m2/m2)**

**Biomass (kg/ha)**

**Fig. 3.**

**Biomass (kg/ha)**

**LAI (m2/m2)**

**Fig. 4.**

.

**LAI (m2/m2)**

**Biomass (kg/ha)**

**Fig. 5.**

**Biomass (kg/ha)**

**LAI (m2/m2)**

**Fig. 6.**

kg/ha

Simulated yield (kg/ha)

Observed yield (kg/ha)

Canola yield (kg/ha)

**Fig. 7.**

Canola yield (kg/ha)

Overall yield

**Fig. 8.**