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Full Length Research Paper

Regression model for the study of sole and cumulative effect of temperature and solar radiation on wheat yield

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The effect of variability in temperature, solar radiation and photothermal quotient were studied under varying planting windows in three wheat genotypes to cope environmental vulnerability. Regression models are regarded as valuable tools for the evaluation of temperature, solar radiation and photothermal quotient effects on wheat yield to bring its resilience to climatic vulnerability. The objective of this study was to evaluate sole and cumulative impact of temperature and solar radiation on spring wheat (*Triticum aestivum* L.) yield using regression modeling approach. The data collected at maturity for grain number, grain weight and grain yield were regressed against mean temperature, solar radiation and photothermal quotient (PTQ) (temperature plus solar radiation) from emergence to anthesis and maturity, using STATISTICA9 software. Scatter-plot regression model was developed at 95% confidence interval with crop data and climate variables. Results indicate direct relationship of yield with solar radiation, cumulative effect of temperature and solar radiation, whereas yield had an inverse relationship with temperature alone. Direct relationship between PTQ and yield parameters confirmed PTQ as crop-yield determinant, thus, its management needs to be done by choosing a more appropriate sowing time and best suited genotypes as an adapted management strategy for farmers under increased climatic vulnerability.

Key words: Photothermal quotient, planting windows, solar radiation, temperature, wheat.

INTRODUCTION

Climatic factors like temperature, solar radiation and rainfall affect crop yield. Changes in climatic variables like rise in temperature and decline in rainfall have been reported by Intergovernmental Panel on Climate Change (IPCC, 2007). Pre- and post-anthesis high temperature and heat had massive impacts upon wheat growth, whereas stress reduced photosynthetic efficiency (Wang et al., 2011). You et al. (2009) observed a significant reduction in yield caused by a rise in temperature; a rise of 1.8°C in temperature caused 3 to 10% reduction in wheat yield. Planting windows and choice of genotypes influenced yield of wheat in rainfed ecologies where crop production is constrained by low rainfall (Ahmed et al., 2010a). The photothermal quotient (PTQ) can be defined as the ratio of total solar radiation in $MJm^{-2}day^{-1}$ to the mean daily temperature minus a base temperature (4.5°C for spring wheat). The impact of climatic variables like temperature, solar radiation and photothermal quotient (PTQ) could be assessed during crop life-cycle and by developing a quantitative relationship between climatic variables and crop yield. Development of models as new adaptation and mitigation strategies by understanding the biophysical impact of climate change on wheat crop growth kinetics has been found to be significant for attaining yield sustainability. Therefore, incorporation of climate data like temperature and solar radiation with crop parameters was needed to develop models to minimize climatic vulnerability. Changes in mean temperature can shorten the time to maturity, thus reducing yield. A few days of temperature above a threshold value, if coincident with anthesis, can significantly reduce yield by affecting subsequent reproductive processes (Wheeler et al., 2000). A significant change in yield of wheat caused

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Abbreviation: PTQ, Photothermal quotient.

by variation in temperature and solar radiation was observed by Li et al. (2010). Similarly, 0.6 to 8.9% reduction in wheat yield per 1℃ rise in temperature has been reported by Lobell and Field (2007). However, Akcura et al. (2005) were of the view that selection of suitable genotypes under various changing climatic scenarios must be evaluated.

Nalley et al. (2009) identified PTQ as a factor that improved the explanatory power of statistical regression models relative to grains per meter square (GM), grain weight (GW) and yield under a climate-change scenario. Similarly, a direct relationship between PTQ and growth of wheat under different planting systems has been reported by Khichar and Niwas (2007). However, Loomis and Amthor (1996) concluded that crop growth and yield were derived from photosynthesis, and were dependent on receipt and capture of solar radiation only. Therefore, to distinguish between roles of solar radiation and PTQ in wheat crop growth and yield development of regression model is essential on the basis of original field data. In the present scenario of climate change, the evaluation of wheat genotypes under variable climatic conditions was essential for yield sustainability. The optimal combination of various inputs to attain sustainable yield can be determined by experimentation and measurement of wheat crop response to climatic factors like temperature and solar radiation. However, experiments are difficult to repeat under a wide range of conditions. Thus, development of regression models provides a valuable tool to analyze the behavior of wheat crop under a wide range of production conditions (Alva et al., 2010). Hence, studies are needed to understand and quantify the crop response and its relationship with various combinations of temperature and solar radiation to determine suitable planting windows for wheat. This is only possible if the canopies are tested under varying levels of temperature and radiation. The practical way to expose crop to variable climatic parameters is to alter the sowing time of the crop within a recommended growing season. Therefore, this study was designed to examine climatic effects on wheat crop by adjusting sowing time for sustainable wheat production with the objectives to (1) determine optimal utilization of climatic resources by matching wheat crop phenological stages with available resources; (2) maximize wheat yield and quality; (3) adjust sowing time based upon available climatic conditions, and (iv) develop a regression model and illustrate its application to predict effects of the climatic variables on grain weight, grains per meter square and yield of wheat crop.

MATERIALS AND METHODS

The present study was conducted in a high rainfall zone of Pothwar, that is, Islamabad, Pakistan (mean annual temperature = 21.3℃; evapotranspiration = 1588 mm; rainfall = 645 to 1000 mm; latitude, 33° 42' N and longitude 73° 10' E, and elevation = 508 masl). The soil series of the study site was Rajar, with great groups ustorthents and soil order entisol. Five different planting windows (PWs) were used to provide variable climatic conditions at anthesis and maturity of wheat in two environments (2008/2009 and 2009/2010). The PWs for three wheat genotypes, namely, Chakwal-50, Wafaq-2001 and GA-2002, are presented in Table 1. The experiments were conducted using a randomized complete-block design, replicated four times (4.5 × 10 m plots with a row spacing of 25 cm). Prior to sowing, the field was kept fallow during summer and plowed once with a soil inverting implement and thereafter thrice with a tractor-mounted cultivator.

Climatic data regarding temperature and solar radiation during the study period were collected from the Meteorology Department of Pakistan (http://www.pakmet.com.pk/). The mean temperature from emergence to anthesis (T1) and to maturity (T2) was calculated by averaging all temperature from germination till anthesis and maturity, respectively. Similarly, solar radiation at anthesis (SR1) and maturity (SR2) was recorded with a solarimeter (SL 100), which was designed to measure the total direct solar radiation and diffuse solar radiation while sum of both these radiations was called as global solar radiation. The Angstrom formula ($H = H_o$ (a + b(n/N'))) was used to relate solar radiation to extraterrestrial radiation and relative sunshine duration, where H_o is extraterrestrial radiation (MJ m^{-2} day^{-1}), N' is the day length (h) and 'a' and 'b' are fitted coefficients; a = 0.21, b = 0.37) (Allen et al., 1998).

The PTQ was calculated using Oritz-Monasterio et al. (1994) procedure; PTQ1 from emergence to anthesis by adding daily PTQs from germination to anthesis; and PTQ2 at maturity. The number of days taken by each genotype from emergence to maturity during two growing environments (2008-09 and 2009-10) among planting windows are presented in Figure 1. All genotypes at maturity were harvested for measurement of grain number per meter square, unit grain weight (g) and grain yield (Kg ha^{-1}).

Statistical analysis

The data recorded were subjected to statistical analyses using STATISTICA 9 (Statsoft, Inc. 2010) software to develop regression models among T1, T2, SR1, SR2, PTQ1 and PTQ2 (Independent variables) with grain number per meter square (GM), unit grain weight (GW) and grain yield as dependent variables. A scatter diagram can be used as a linkage between environment and yield parameters as reported by Feiziasl et al. (2010). Two-dimensional scatter plots showed a relationship between two variables X and Y (example, T1 and GM). The regression analysis was performed using a confidence interval of 95%.

RESULTS AND DISCUSSION

An inverse correlation between pre-anthesis temperature and grain number was observed in the regression scatter plot of grains per square meter against T1 (pre-anthesis temperature) (Figure 2a). The highest number of grains was recorded between 18 to 20℃ temperature (R^2 = 0.89). The regression equation obtained was GM = 5308.99 + 623.73 (T1) (0.95 confidence interval) with a significant slope at p<1%. The results indicate a strong relationship between optimum pre-anthesis temperature and grain number, which correlated with grain yield. Thus, optimal temperature from emergence to anthesis resulted to translocation of photosynthate to grain effectively. Similarly, response of grain weight to T1 depicted the maximum grain weight at 17℃ [regression equation: GW = 0.034 + 0.0037(T1)]. The relationship between pre-anthesis mean temperature and grain weight was positive

Table 1. Planting windows (PW's) for wheat genotypes at Islamabad during 2008 to 2009 and 2009 to 2010.

PW	Islamabad	
	2008-2009	2009-2010
PW1	20-October	23-October
PW2	26- October	05-November
PW3	05-November	19-November
PW4	19- November	27-November
PW5	05-December	10-December

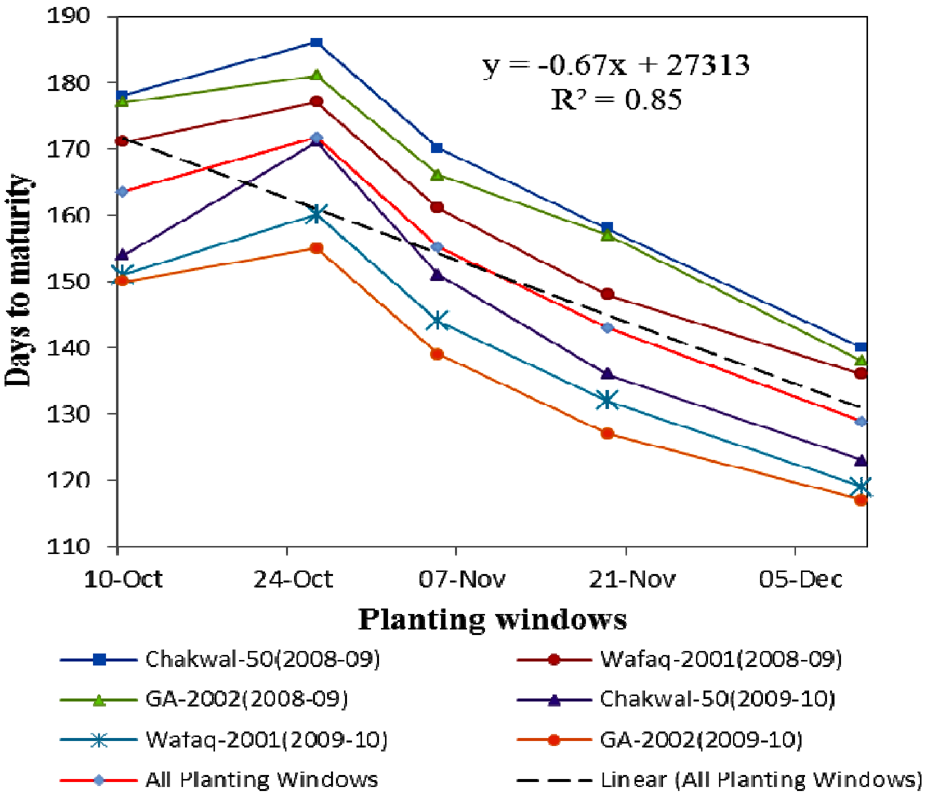

Figure 1. Days to maturity for three wheat genotypes among five planting windows during two growing environments (2008-2009 and 2009-2010) with regression trend for average days to maturity among all planting windows and genotypes.

(R^2 = 0.78) but up to optimum level, that is, 17°C (Figure 2b). Further rise in temperature after optimum level led to shrunken grains, resulting in reduced grain weight. Similarly, yield was directly related to temperature from emergence to anthesis stage (Figure 2c). However, further rise in temperature above 25°C caused yield stagnation. The regression equation for yield in relation to T1 was Y = 3284.75-5.97(T1), with a significant coefficient of determination (R^2 = 0.79). A decline in GM, GW and yield was observed with an increase in temperature from germination till maturity (T2) (Figures 2d to f). The adverse effect of high temperature on yield could partially be modified by preventive strategies, such as earlier sowing. Biological clock acceleration because of the increased temperature hastened development and reduced the growing period between emergence and maturity. The regression equations obtained at 95% confidence interval for GM, GW and grain yield (YLD) were: GM = 47367.06 - 1356.28(T2) (R^2 = 0.90), GW = 1.05 - 0.02 (T2) (R^2 = 0.87) and YLD = 4542.37 - 57.86(T2) (R^2 = 0.85). The regression model showed a negative trend with a unit increase in temperature from emergence to maturity. Therefore, the declining trend for GM, GW and grain yield (YLD) could be because of a rise in temperature

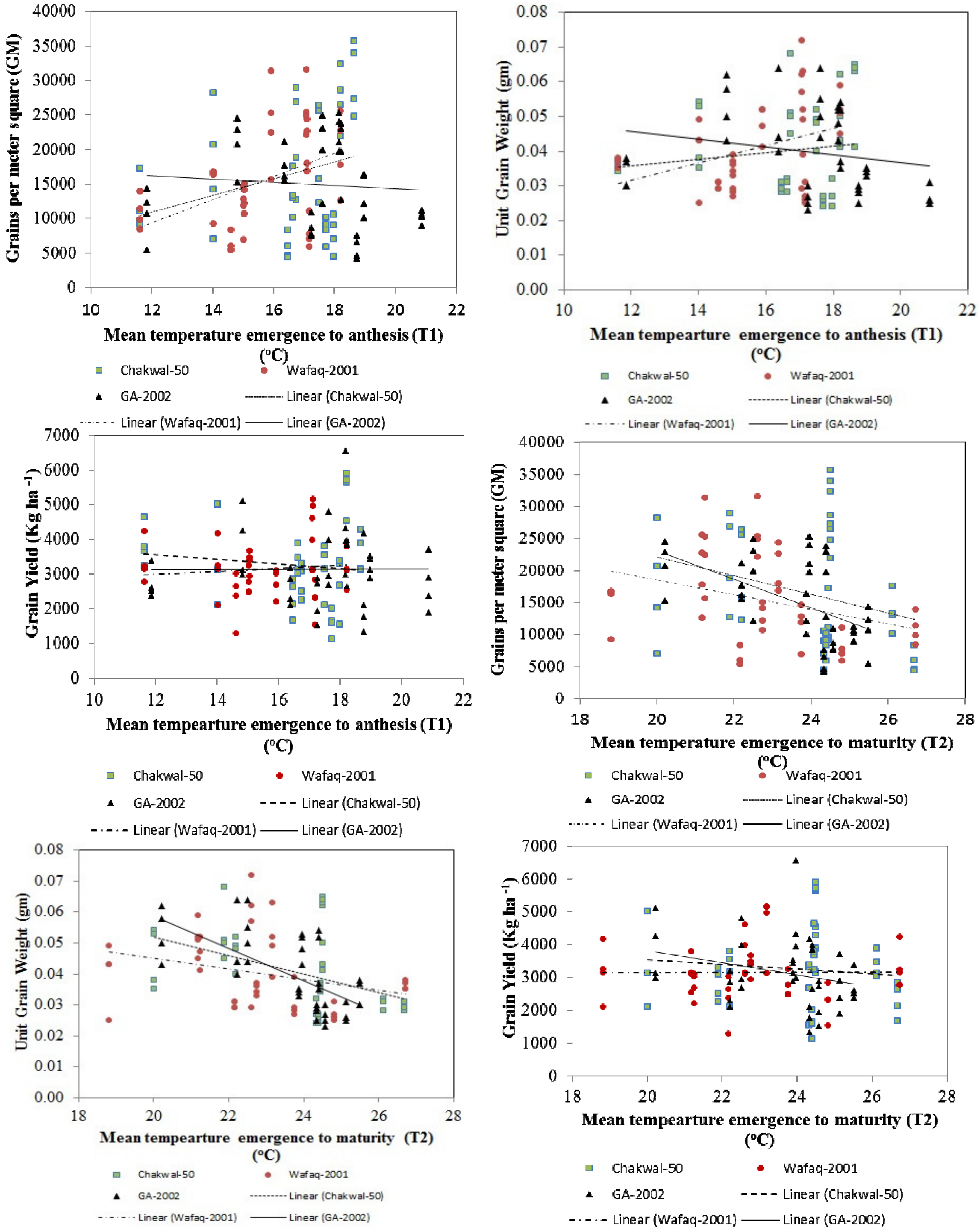

Figure 2. Regression plot of (a and d) grains per meter square (GM), (b and e) unit grain weight (GW) and (c and f) yield (Kg ha^{-1}) against mean temperature (°C) from emergence to anthesis (T1) and maturity (T2).

from emergence to maturity, which led to reduced growth cycle, deceased dry matter accumulation and yield (Fulco and Senthold, 2006). The significant negative trend of GM and GW with a rise in temperature showed that elevated temperature had an adverse effect on crop growth and development. Gate (2007) concluded that temperatures above 25℃ significantly reduced grain weight, whereas Kalra et al. (2008) further elaborated that wheat yields fell by 0.2 to 0.5 t ha^{-1} ℃$^{-1}$ rise in temperature. Similarly, in the pre-sent study, a decrease in grain per square meter could be caused by high temperature near heading. Hays et al. (2007) were of the view that stress caused by increased temperature restricted growth and productivity, particularly during reproductive crop stages. Similarly, a reduction in grain weight caused by a rise in temperature resulted in reduced drymatter accumulation; however, exposure of crops to higher than optimum temperature resulted in earlier maturity because of the faster accumulation of growing degree days. Fluctuation in temperature from germination to maturity affected the grain developmental period of wheat crop. The increased temperature shortened the grain-filling period in wheat (Wheeler et al., 1996), whereas its effect would probably be detrimental in Mediterranean-type environments, where high summer temperatures coupled with water stress had reduced crop production (Rosenzweig and Tubiello, 1997). The extremes detrimental effects of temperature on wheat crop of rainfed agriculture could be minimized by sowing crop at best time. However, best sowing time need to be recommended by modeling climatic variables (rainfall, temperature, solar radiation and PTQ) with crop yield components. Since, in our study, best results were obtained for planting window two (PW2), sowing was recommended at this time period for yield sustainability in rainfed agriculture.

Solar radiation is an important environmental factor that brings positive changes in the crop growth by altering leaf architecture and light partitioning. Similarly, solar radiation activates the photosystem by which light reaction of photosynthesis starts and electrons generated by photolysis of water move to produce energy carriers (example, NADPH, FADPH and ATP). The scatter plot regression model showed a positive relationship between GM, GW and grain yield with SR1 and SR2 (Figure 3). The regression models obtained for GM, GW and yield (YLD) with SR1 were GM = -19542.51 + 29.53 (SR1); GW = -0.15 + 0.0005 (SR1), YLD = -1516.47 + 3.9549 (SR1) respectively. The results depict positive correlation of SR1 with yield because of good source-sink activity. Likewise, positive association was found between crop yield parameters (GM, GW and yield) and SR2. The study indicates that increased solar radiation from emergence till maturity had a significant impact on yield. The regression model equation showed a direct relationship of SR2 and GM, GW and yield (GM = -21272.63 + 19.90 (SR2), GW = -0.1551 + 0.0003 (SR2) and YLD = -1575.8369 + 2.57 (SR2)). The study shows a significant increase in GM, GW and yield with increased solar radiation. Significant response of crop to solar radiation might have been caused by modification of duration of photosynthesis. Sowing time used in the present study caused variability in solar radiation, which ultimately affected the duration of crop growth because of differential partitioning of light. Crop exposure to favorable environmental conditions for an optimum number of days helped in stand establishment and increasing yield. Favorable environmental conditions led to optimum time of flowering, therefore, avoiding the detrimental effects of abiotic stresses. Hence, anthesis-time management by sowing crop under different time periods could be an adaptation strategy for optimum yield under changing climate (Richards, 2006). In the present study, results clearly indicated that variations in environmental factors caused changes in crop yield. Thus, the present investigation emphasized on management of environmental resources by using field and modeled information to shift crop sowing time for yield sustainability under changing climate.

Photothermal quotient portrayed the combined effect of solar radiation and temperature on crop yield. Grain numbers per meter square (GM), grain weight (GW) and grain yield (Kg ha^{-1}) were positively related to PTQ1 with R^2 of 0.88, 0.66 and 0.59, respectively. The regression equations indicated that with a unit change in PTQ1, increased at a rate of 314.20, 0.0049 and 49.88, respectively, GM, GW and yield. The regression model obtained between PTQ1 and yield components clearly indicated that PTQ1 was related to GM, GW and yield in a positive manner when all other resources remained optimum throughout the crop growth period. The regression model obtained was GM = -28518.88 + 314.20 (PTQ1), GW = -0.287 + 0.0049 (PTQ1) and YLD = -3814.91 + 49.88 (PTQ1) at 0.95 confidence interval (Figure 4a to c). The scatter plot obtained for PTQ2 indicated its positive correlation with GM, GW and grain yield (Kg ha^{-1}) (Figure 4d to f). The regression models obtained for PTQ2 vs. yield parameters indicated that PTQ was a determinant factor that affected yield significantly (GM = -27382.86 + 237.40 (PTQ2; GW = -0.27 + 0.0037 (PTQ2): and YLD = -2582.43 + 31.87 (PTQ2)). The PTQ from emergence to maturity determined the overall impact of climate variables on crop growth. GM, GW and yield recorded for late planting windows remained significantly lower than for earlier planting windows like PW1, PW2 and PW3. Significant positive association was observed for grains m^{-2} vs. PTQ1 and PTQ2 (R^2 = 0.97 and R^2 = 0.90 respectively). A positive linear trend was recorded for GW and PTQ; this was also confirmed by Ahmed et al. (2010b). Similarly, maximum grain weight recorded under maximum PTQ availability from emergence to maturity led to optimum photosynthate accumulation and their translocation to grains.

Meanwhile, factors that contribute to yield must be incorporated for genotype selection under drought to cope with the fluctuating seasonal variability. Since PTQ affected grain weight decisively, all other resources remained optimum throughout the crop life cycle (Khichar and Niwas 2007); therefore, it use in model development could boost crop productivity. Yield was strongly linked with PTQ1 and PTQ2 (Figure 4). The yield was highest at maximum PTQ, and dropped significantly with a decreased PTQ. This declining trend could be because of unavailability of optimum environ-mental conditions. Therefore, increased yield in the present study could be due to active utilization of avail-able resources at critical stages by crop plants of early sown wheat crop. However, association of photothermal quotient models

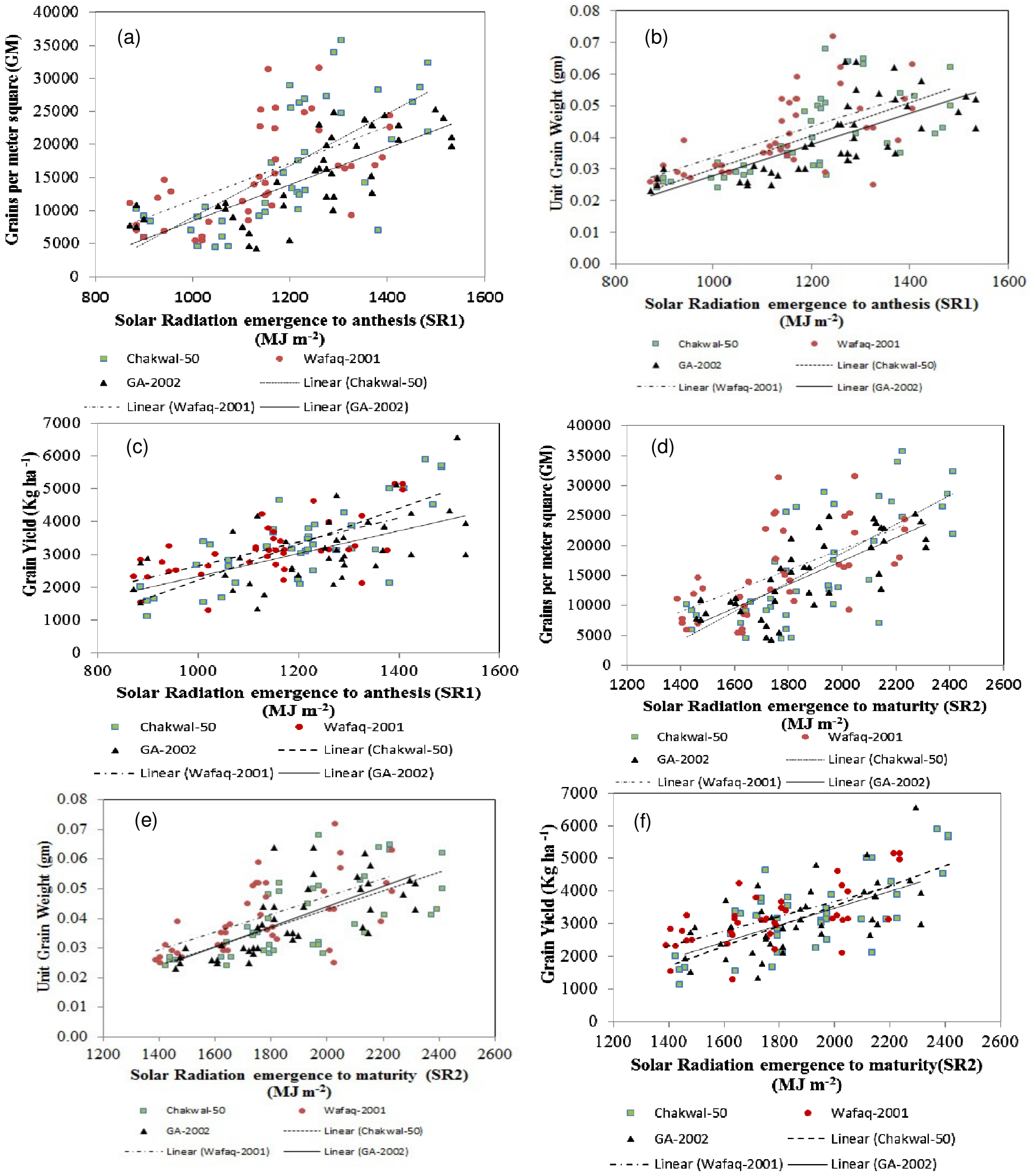

Figure 3. Regression plot of (a and d) grains per meter square (GM), (b and e) unit grain weight (GW) and (c and f) yield (Kg ha^{-1}) against total solar radiation (MJ m^{-2}) from emergence to anthesis (SR1) and maturity (SR2).

with grain development and yield compo- nents needs to be documented to build a comprehensive model between photothermal quotient and crop growth and development. Because PTQ elaborated the combined effect of temperature and solar radiation on crop yield, it could be considered as a limiting factor, which controls overall crop growth and development.

Conclusion

Modeling environmental resources, such as temperature and solar radiation, enhanced yield of crop by adaptation strategies. The models in conjunction with actual field data are useful in integrating available knowledge, in identifying gaps that require further research and in a few

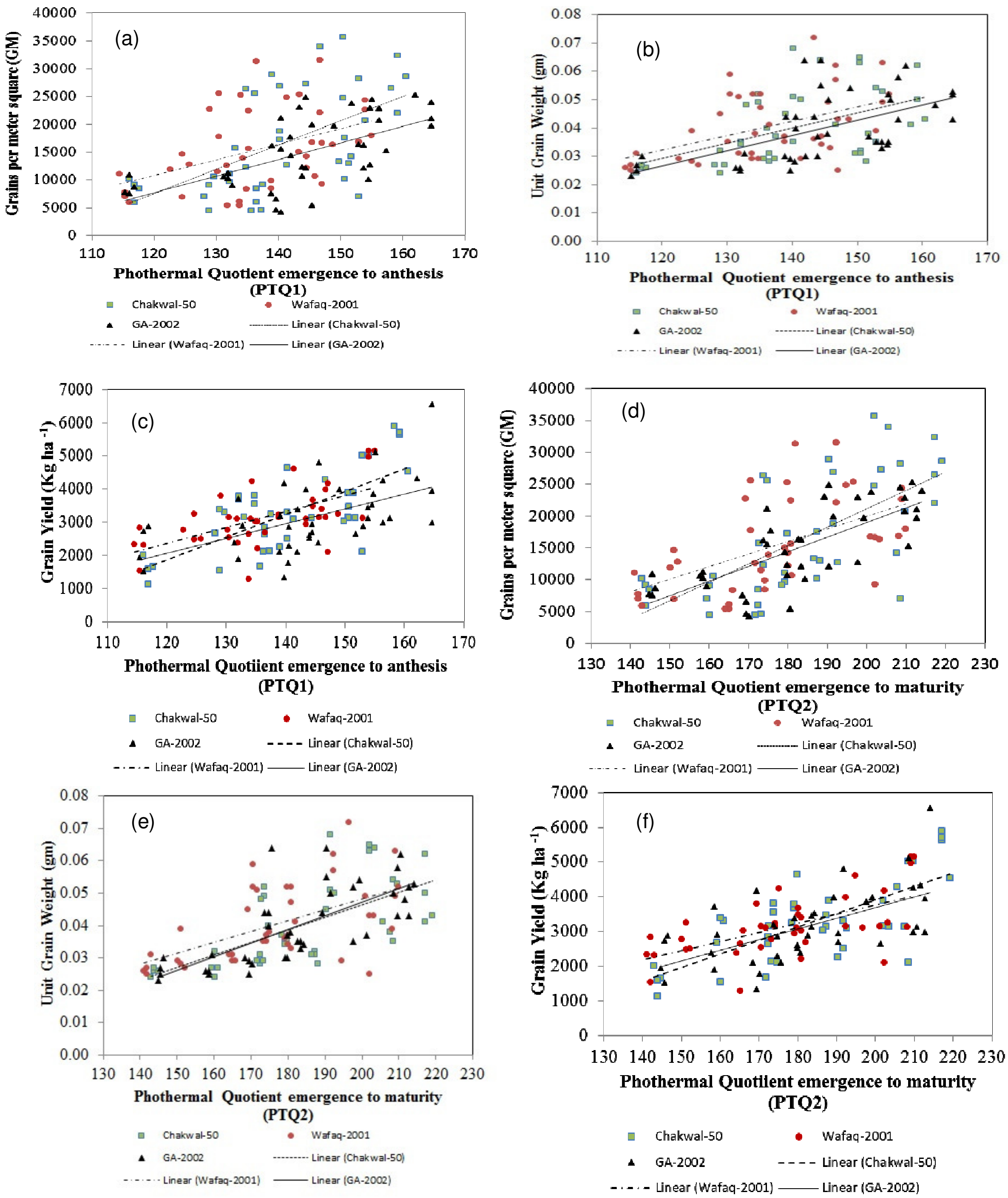

Figure 4. Regression plot of (a and d) grains per meter square (GM), (b and e) unit grain weight (GW) and (c and f) Yield (Kg ha^{-1}) against photothermal quotient (MJ m^{-2} day^{-1} ℃$^{-1}$) from emergence to anthesis (PTQ1) and maturity (PTQ2).

cases predicting potential crop productivity as well as influence of environment on crops. The current observed trends in climate change would certainly enhance the role of modeling for managed agro-ecosystems and for natural bio-systems in relation to their potentials for climatic extremes. Similarly, selection of genotypes that are more adaptive to variable temperature, solar radiations and PTQ needs to be considered in the modeling strategies using traits like early and late maturity, drought tolerance and tiller inhibition.

These features can improve genotype interaction with environment by utilizing resources effectively and could bring sustainability in yield under extreme climatic vulnerability.

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