GREEN AND BLUE WATER REQUIREMENTS FOR SUSTAINABLE PAKISTAN'S STAPLE CROP PRODUCTION UNDER FUTURE CLIMATE CONDITIONS

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ABSTRACT

Sustainable wheat production is crucial for economic and food security of Pakistan; since wheat is a staple for masses and millions of agricultural workers rely on its production for employment and livelihood. In this work, green and blue water requirements were projected to sustain future wheat production in Punjab, Pakistan using the statically bias-corrected climate change projections from nine global circulation models by the end of 2080. Climate projections envisaged substantially hotter and drier future wheat growing season featuring significant yield losses. During the 2030s (2021 – 2050), the seasonal cumulative crop evapotranspiration (ET) and irrigation requirements declined due to growth span shortening induced by the moderate warming; whereas, during the 2060s (2051 – 2080), they both increased despite a significant growth span shortening caused by intense warming. The future wheat production was more irrigation-dependent since the green water contribution would be limited. Future wheat total water footprint (TWF) continuously increased; implying that the apparent ET decrease would not necessarily result inTWFs reduction. The projected green water footprints (GWF) declined and inclined during the 2030s and 2060s, respectively, indicating higher green water availability during 2nd half of the 21st century. During the 2030s, despite the limited green water availability, the blue water footprint (BWF) increments were marginal due to moderate warming. The BWF increments were higher during the 2060s compared to the 2030s; highlighting that higher green water contribution would not suffice warming driven 2060s-ET increments. The CO_2 enrichment effects showed promises to partially compensate for the detrimental climate change impacts over wheat yield and WFs; nevertheless, the reliability of such estimates demands a further in-depth examination of crop yield responses to climate change under field conditions.

Keywords: Climate change, Water footprint, Wheatyield, Aquacrop

1. INTRODUCTION

In the 21st century, one of the major concern faced by the scientific community is to conceptualize climate change influences on irrigated agriculture and food production systems (Luo et al., 2015). An increased CO_2 concentration could result in yield increment; whilst climate warming could accelerate the crop phonological development and evapotranspiration rates, thus compromising the potential yields. Similarly, higher irrigation water demands originating from the frequent droughts could also limit crop production (Ahmed et al., 2013; Bocchiola et al., 2013).

Pakistan is particularly susceptible to such adverse climate change impacts due to its over-reliance on irrigated agriculture; constantly diminishing freshwater resources; exponential population growth and low adaptation capacity(Ali et al., 2017; Khan et al., 2016).Wheat is the staple crop; accounting for up to 50% of daily calorific intake and its availability and accessibility dictates the country's food security conditions.

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However, wheat cultivation area and yield per hectare had been dwindling since 2003 mainly because of ineffective use of scanty water supplies and rapid climate change(Arshad et al., 2017; Qureshi, 2011).

Since climate change affects both the crop water usage and yield; therefore, it would be logical to examine both the components at the same time. The water footprint approach could serve this purpose by comprehensively identifying the inter-relationship between the crop yield and water use under the changing climate. (Mekonnen and Hoekstra, 2011; Sun et al., 2012).

For the crop production process, the total water footprint refers to the volume of water used per unit weight of the yield production. At present Pakistan is listed among the countries where substantially huge amounts of irrigation or blue water is being used per ton of wheat production as compared to the global average, particularly in the Punjab province. (Khan et al., 2016; Mekonnen and Hoekstra, 2010; Mekonnen and Hoekstra, 2011). This study was aimed at predicting the future climate change effects, on the wheat yield and the associated blue and green water footprints, in Punjab, Pakistan. By analysing the future yield trends along with the water footprints, the results are anticipated to be helpful in devising an appropriate water management strategy to obtain the optimum wheat yields from the limited water resources.

2. METHODS

2.1 Study Area

The district Faisalabad located in central Punjab was selected for the study due to the availability of the experimental data from the Regional Agro-Met (RAMC) site managed by the Pakistan Meteorological Department (PMD). The climate of the study area is semi-arid with more than 70% of the annual rainfall occurring from June to September. Average seasonal maximum and minimum temperatures ranged from 23 °C to 27 °C and 3 °C to 8 °C, respectively, whereas seasonal cumulative rainfall varied from 85 mm to 210 mm. Well-drained, sandy clay loam is the dominant soil texture in this area (Iqbal et al., 2011; Khan et al., 2015).

2.2 GCM and future climate scenario

Nine GCMs, listed in table 1, were chosen to project the future climate of the study area. Daily GCM outputs including maximum temperature (T_{max}), minimum temperature (T_{min}), relative humidity (RH), wind speed (u_2), solar radiations (R_n) and precipitation (P) forced under two representative concentration pathways (RCPs) scenarios: 4.5 and 8.5 during two future time slices: the 2030s (2021 − 2050) and 2060s (2051 − 2080) were included in the study.

Coarse-resolution GCM-outputs were subjected to the commonly followed procedure of quantile mapping (QM) (Eum and Cannon, 2017; Miao et al., 2016) to reduce biases in GCM historic and future simulations. A 30-year daily weather data for the baseline period of 1980 to 2010 including T_{max}, T_{min}, RH, u_2, R_n and P were collected from the PMD for weather station located in the study area. The QM procedure was applied at the daily time step to statistically bias-correct the GCM outputs of six major climate variables during the baseline period as well as during the 2030s and 2060s.

2.3 Aquacrop calibration and simulation

FAO developed Aquacrop v 5.0 water-driven, crop growth and yield simulation model was calibrated using the experimental data collected at the RAMC Faisalabad site from 2004 to 2017. Figure 1 shows the calibrated model performance evaluated based on Nash-Sutcliffe efficiency (NSE), root mean square error (RMSE) and index of agreement (IoA) (Greaves and Wang, 2016; Paredes et al., 2015; Toumi et al., 2016).

Table 1. Summary of GCMs used in this study

GCM	Institution	Horizontal Resolution
BCC-CSM-1.1	Beijing Climate Centre, China Meteorological Administration	~1.25°×1.875°
BNU-ESM	College of Global Change and Earth System Science, Beijing National University	~2.8°×2.8°
GFDL-ESM2M	NOAA/Geophysical Fluid Dynamic Laboratory (GFDL)	~2.0°×2.5°
CCSM4	US National Centre for Atmospheric Research	~0.9°×1.25°
HadGEM2-ES	UK - Meteorological Office – Hadley Centre	~1.25°×1.875°
inmcm4	Russian Institute of Numerical Mathematics (INM)	~1.5°×2.0°
MIROC5	University of Tokyo, Japanese National Institute for Environmental Studies (NIES), and Japan Agency for Marine-Earth Science and Technology (JAMSTEC)	~1.4°×1.4°
MPI-ESM-LR	Max Plank Institute of Technology (low resolution)	~1.9°×1.875°
MPI-ESM-MR	Max Plank Institute of Technology (mixed resolution)	~1.9°×1.875°

Statistically bias-corrected daily GCM outputs were fed into the Aquacrop to simulate the future wheat yield responses to climate change. Two simulation sets were run with and without the inclusion of CO_2 enrichment effects. The present day and projected future CO_2 concentration used in the two simulation sets are shown in table 2. Wheat sowing date was fixed as 20 November and an automatic irrigation schedule was generated by the Aquacrop when 50% of the total available water in the soil has been depleted.

Table 2. CO_2 concentrations used for future wheat yield simulation

Duration	RCP 4.5	RCP 8.5
2004 – 2017 (Baseline)	~390 ppm	
2021 – 2050 (2030s)	415 ~ 485 ppm	420 ~ 538 ppm
2051 – 2080 (2060s)	490 ~ 530 ppm	549 ~ 750 ppm

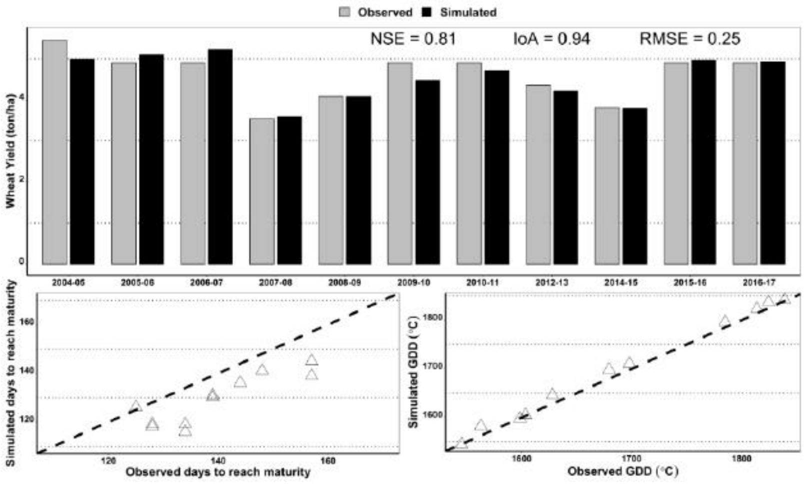

Figure 1. Results of the model calibration

2.4 Wheat water footprint

The blue and green water footprints of the wheat crop were estimated by following the calculation framework proposed by Hoekstra et al. (2009):

$$GWF = \frac{CWU_G}{Y} = 10 \times \frac{ET_G}{Y} \quad (1)$$

$$BWF = \frac{CWU_B}{Y} = 10 \times \frac{ET_B}{Y} \quad (2)$$

$$TWF = \frac{CWU_T}{Y} = 10 \times \frac{ET_T}{Y} \quad (3)$$

where *GWF*, *BWF*and*TWF*, are the green, blue and total water footprints (m^3/ton); CWU_G, CWU_B and CWU_T are the green, blue and total water consumption (m^3/ha) per unit area; ET_G, ET_B and ET_T represent the cumulative green, blue and total evapotranspiration (mm) during the growing season; factor 10 is to convert the water depths (mm) into volumetric water per land surface (m^3/ha); *Y* is the crop yield (ton/ha).

3. RESULTS AND DISCUSSION

3.1 Future climate change projection

Mean, median, and variability of GCM-projected monthly, seasonal and annual T_{max}, T_{min}, R_n and P, after bias correction, are shown as box plots in figure 1. The boxes in figure 1 and afterwards represent the interquartile range (IQR), the whiskers extend up to 1.5 times the IQR, the dot and horizontal line inside the box represent mean and median, respectively, and outliers are shown as hollow dots outside the boxes. The monthly variations are plotted on left y- axes; whereas, the seasonal and annual variations are plotted on right y-axes.

Compared to the baseline, seasonal T_{max} and T_{min} rise, averaged across 9 GCMs for RCP 4.5, was 1 to 3.5 °C and 4 to 6 °C, respectively; whilst under RCP 8.5, it was 1.6 to 5 °C and 5 to 8 °C, respectively, by end of the 2060s. Similarly, annual T_{max} and T_{min} increments of 1 to 2 °C and 1.5 to 2.5 °C for RCP 4.5; and 1.5 to 2.7 °C and 1.9 to 3 °C for RCP 8.5 were shown by the end of the 21st century.

Majority of GCMs predicted declining or unchanged P while some GCMs envisaged rising P tendencies; the ensemble seasonal and annual P decreased with respect to the baseline. Contrary to higher seasonal climate warming, future drying was pronounced at the annual scale. For RCP 4.5, seasonal P decline was notably higher than 8.5; while the annual P decline remained almost the same under the two RCPs during both time slices. On average, 45 to 53% and 13 to 30% decrease in seasonal P; whereas 56 to 60% and 53 to 59% decrease in annual P was predicted by the end of the 21st century under the RCP 4.5 and 8.5, respectively. The R_n also demonstrated continuously declining tendencies in the future regardless of time scale, RCP or time slice.

3.2 Climate change impacts on wheat evapotranspiration and irrigation requirement

The average wheat seasonal cumulative evapotranspiration (ET) and irrigation requirement recorded at the RAMC Faisalabad site from 2004 to 2017 were 285 mm and 188 mm, respectively. Figure2 presents variations in the Aquacrop simulated seasonal ET and irrigation requirement with respect to the baseline for the two RCPs and the two time slices. From here on the term “baseline” refers to 2004 to 2017 period for which the wheat experimental data were available.

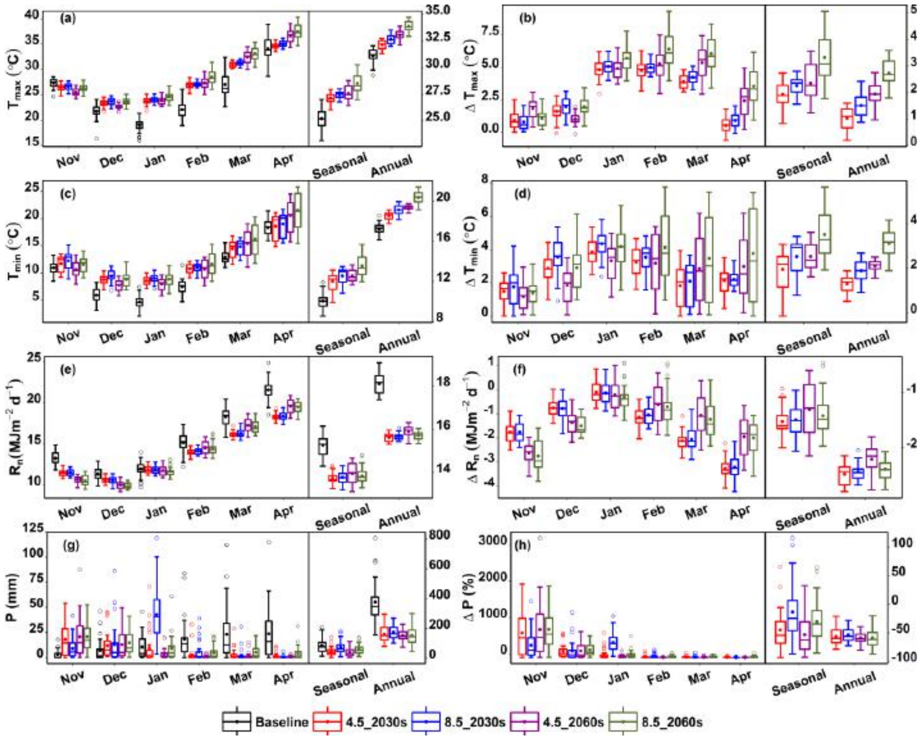

Figure 2. Projected future T_{max}, T_{min}, R_n and P

Projections suggested that seasonal ET and irrigation requirement would decline in the future which seems odd given that climate warming is often associated with accelerated ET rates and consequently higher irrigation requirements. Climate warming cut short the average wheat growth span. A growth-span reduction of 10 to 12 days for RCP 4.5 and 13 to 20 days for RCP 8.5 was shown by the end of the 2060s (results not presented here). This could explain the unexpected decline in the seasonal cumulative ET and irrigation requirement.

The negative baseline ET change during the 2030s was comparatively lower for the RCP 8.5 (-11 mm) than the 4.5 (-20 mm). During the 2060s, despite a significantly shortened growth span, higher warming resulted in an increased baseline-ET without the CO_2 enrichment. The GCM-ensemble median ET rise during the 2060s was almost the same for both the RCPs (13 to 15 mm), but the IQR of ET change for RCP 8.5 was higher than that of 4.5 indicating a higher increasing tendency. Including the CO_2 enrichment lessen the severity of the aforementioned ET trends but overall the role of CO_2 concentration in determining the ET trends was somewhat limited.

Changes in baseline irrigation water requirement followed a similar pattern as that of the mentioned ET trends. During the 2030s, the baseline median irrigation requirement declined (-27 mm); whereas, during the 2060s it increased (+16 mm) almost similarly for both the RCPs at the baseline CO_2 level. Elevating the future CO_2 concentrations did not produce any noticeable difference than from its counterparts. Results suggested that frequent irrigations would be necessary to compensate for the warming-driven ET rates during a shortened growth span in the second half of the 21st century.

3.2 Climate change impacts on wheat yield

The average baseline wheat yield was 4.6 ton per hectare (ton/ha). Projected wheat yield changes during the 2030s and 2060s under the two RCPs with and without the inclusion of CO_2 enrichment are shown in figure 3. Moderate and severe negative impacts on wheat yield were detected, excluding the CO_2 enrichment effects, for both RCPs during the 2030s and 2060s, respectively.

During the 2030s, for both RCPs, the GCM-ensemble median wheat yield decline was almost same (10 to 15%); whereas, during the 2060s, it was 11 to 18% for RCP 4.5 and 11 to 20% for RCP 8.5 at the baseline CO_2 concentrations level of 390 ppm. Rising the future CO_2 concentrations from 415 to 530 ppm under RCP 4.5 and 420 to 750 ppm under RCP 8.5 by end of the 2060s; the corresponding negative climate change impacts over wheat yield were partially and fully compensated. Moreover, despite the severe warming under RCP 8.5 slight increases in wheat yields (8 to 17%) were shown during the two time slices. This implied that doubling the atmospheric CO_2 concentration has the potential to negate the adverse warming impacts.

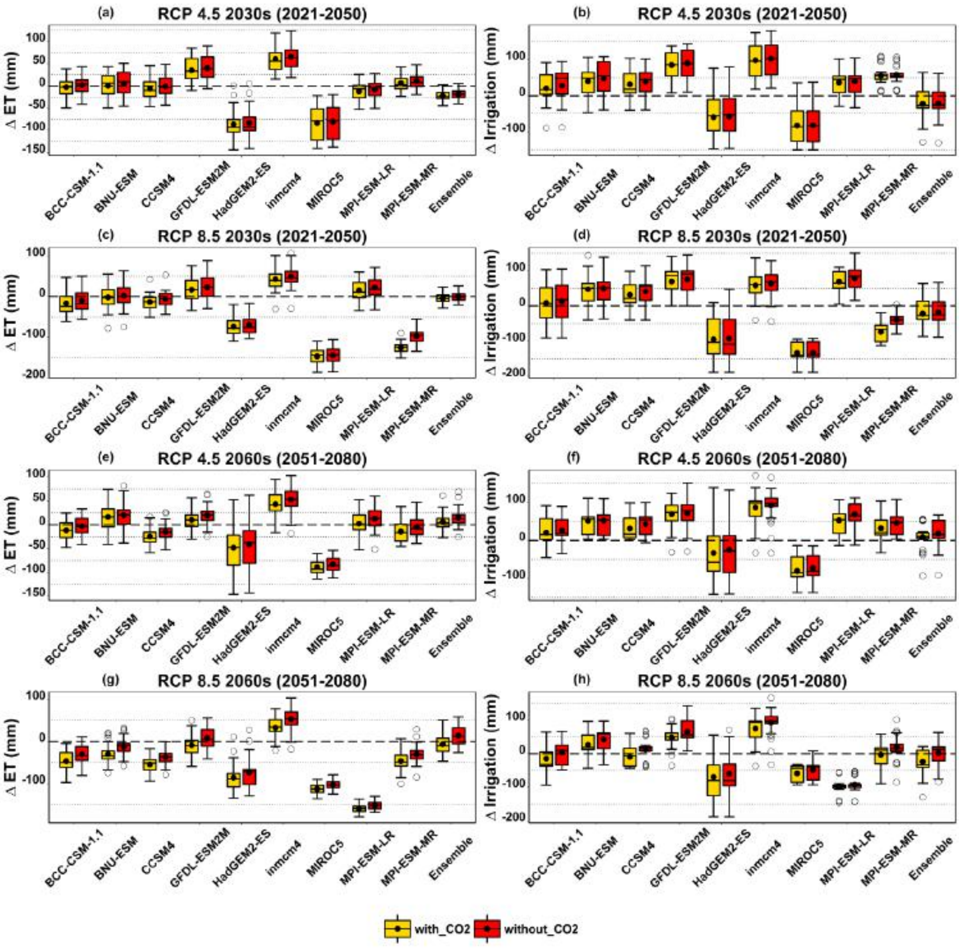

Figure 2. Projected change in wheat seasonal cumulative ET and irrigation requirement

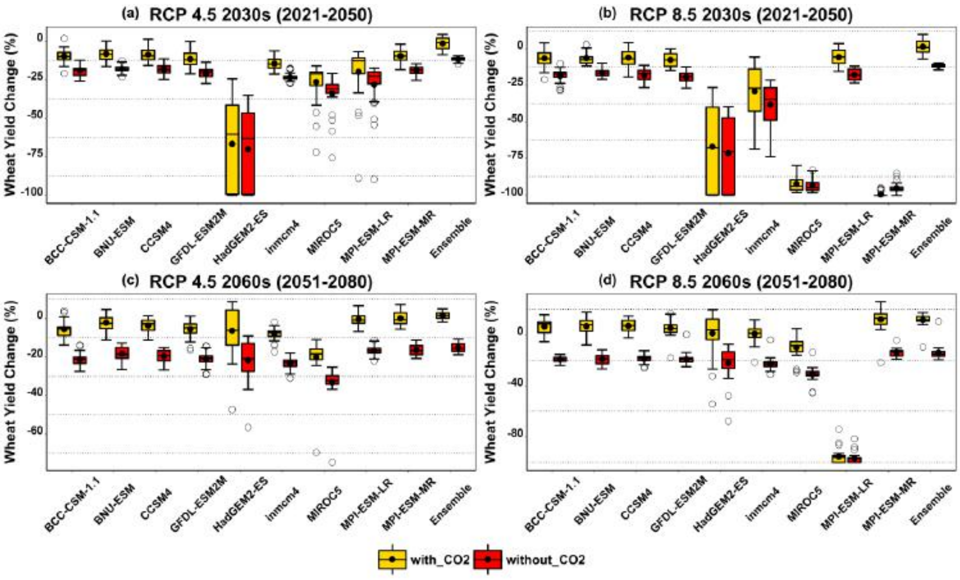

Figure 3. Projected change in wheat yield

3.3 Climate change impacts on wheat water footprint

Baseline average GWF, BWF and TWF were 210, 407, and 617 m^3/ton, respectively. Figure 4 shows the baseline wheat GWF, BWF and TWF variations, averaged across nine GCMs, with and without the inclusion of CO_2 enrichment effects during the 2030s and 2060s for the RCP scenarios. At baseline CO_2 concentration the three wheat-WFs mostly followed inclining trends. Furthermore, the increase in 2060s-WFs was notably higher than the 2030s-WFs increments irrespective of the RCP scenario. Wheat WFs were improved under the enhanced CO_2 concentrations. Positive CO_2 enrichment effect on the WFs was negligible during the 2030s but was notably higher during the 2060s particularly under RCP 8.5. It can be concluded from the IQR and whiskers of figures5 - 7 boxplots that elevated CO_2 concentrations had the potential to mitigate the adverse warming impacts.

Despite having similar change trends, change magnitudes of the three WFs were not the same. For example, the 2060s-GWFshowed a promising rise under both the RCPscompared to the 2030s-GWF rise; indicating higher green water availability during the 2060s wheat season. According to the projected changes in seasonal rainfall, the 2060s duration featured moderate rainfall declines with intense rainfall events. This could explain the more green water availability during the 2060s.

Contrary to the GWF, the rises in BWF and TWF during the 2060s were higher than those of the 2030s. This indicated higher blue water consumption per unit of the crop production which would ultimately lead to higher total water consumption (irrigation + rainfall). Our results suggested that despite the limited green water availability during the 2030s, the increments in blue water consumption would be marginal due to moderate warming. Whereas, during the 2060s, the apparently higher green water contribution would not suffice the warming driven ET increments resulting in higher blue water consumption per unit of wheat production.

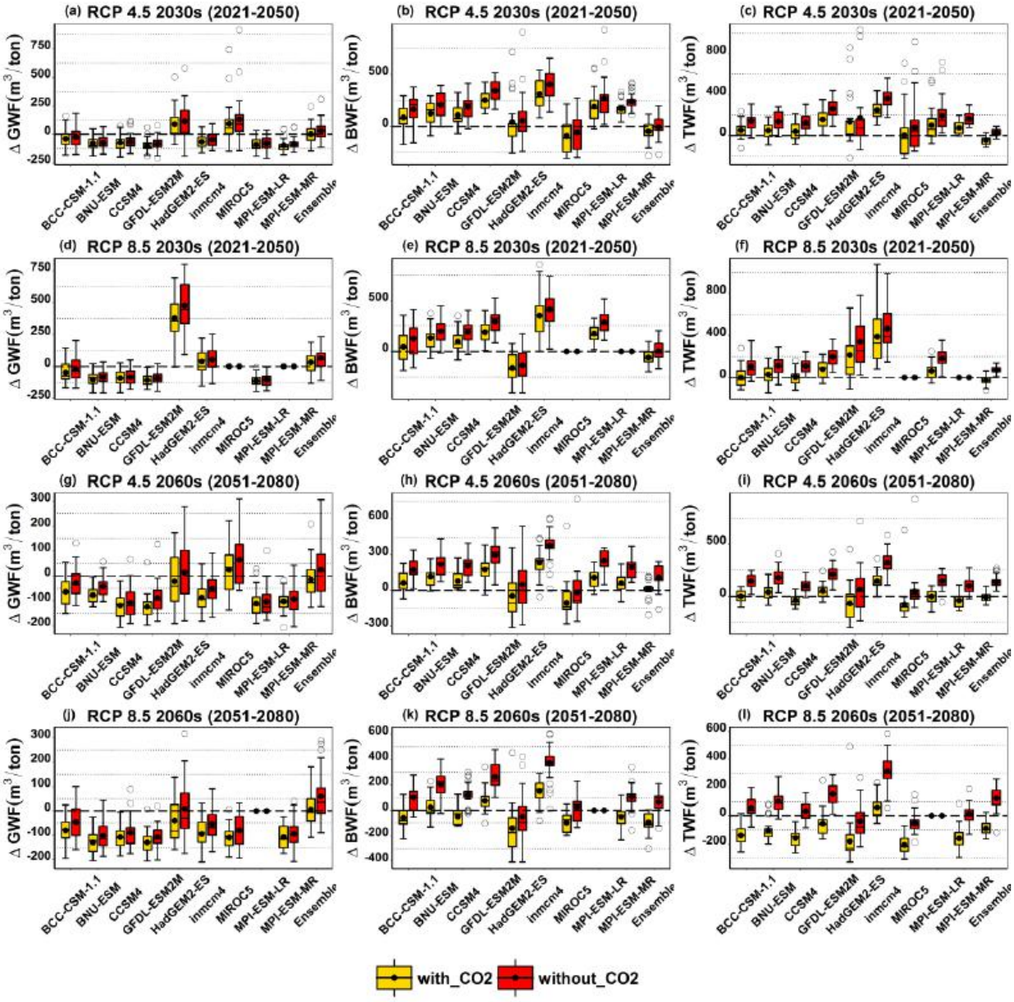

Figure 4. Projected change in wheat green, blue and total water footprints

4. CONCLUSIONS

Statistically bias-corrected ensemble outputs from 9 GCMs clearly showed warning signs, in terms of both T_{max} and T_{min}, respectively, during the 2030s (2021 – 2050) and 2060s (2051–2080) as compared to the baseline (1980 – 2010) at the annual and wheat seasonal scale in Punjab, Pakistan. Probabilities of receiving less seasonal and annual rainfall amounts were also projected. Probable temperature rise accelerated crop phenological progress resulting in growth span and yield reduction of 10 to 20 days and 11 to 20% respectively, by the end of the 2060s. During the 2030s, the seasonal cumulative ET and irrigation requirements declined due to growth span shortening induced by the moderate warming; whereas, during the 2060s, they both increased despite a significant growth span shortening due to intense warming. The three WFs continuously increased indicating profound climatic influences on the crop ET rates and irrigation requirements. The sustainable future wheat production was more dependent on blue water availability. The green water contribution was lower during the 2030s and higher during the 2060s compared to the baseline. Despite the limited green water availability during the 2030s, the BWF increments were marginal due to moderate warming. Whereas, during the 2060s, the apparently higher green water contribution did not suffice the warming-driven ET increments resulting in higher BWFs. The CO_2 enrichment effects showed promises to partially compensate for the detrimental climate change impacts over wheat yield and WFs. The elevated CO_2 concentration of 530 ppm showed limited, and 750 ppm featured strong mitigation role in sustaining and improving future wheat yields and WFs; however, the reliability of such estimates demands a further in-depth examination of crop yield responses to climate change under field conditions.

5. REFERENCES

Ahmed, M., Asif, M., Sajad, M., Khattak, J. Z. K., Ijaz, W., Wasaya, A., and Chun, J. A. (2013). Could agricultural system be adapted to climate change?: A review. Australian Journal of Crop Science 7, 1642-1653.

Ali, S., Liu, Y., Ishaq, M., Shah, T., Abdullah, Ilyas, A., and Din, I. (2017). Climate Change and Its Impact on the Yield of Major Food Crops: Evidence from Pakistan. Foods 6, 39.

Arshad, M., Amjath-Babu, T., Krupnik, T. J., Aravindakshan, S., Abbas, A., Kächele, H., and Müller, K. (2017). Climate variability and yield risk in South Asia's rice-wheat systems: emerging evidence from Pakistan. Paddy and Water Environment 15, 249-261.

Bocchiola, D., Nana, E., and Soncini, A. (2013). Impact of climate change scenarios on crop yield and water footprint of maize in the Po valley of Italy. Agricultural Water Management 116, 50-61.

Eum, H.-I., and Cannon, A. J. (2017). Intercomparison of projected changes in climate extremes for South Korea: application of trend preserving statistical downscaling methods to the CMIP5 ensemble. International Journal of Climatology 37, 3381-3397.

Greaves, G., and Wang, Y.-M. (2016). Assessment of FAO AquaCrop Model for Simulating Maize Growth and Productivity under Deficit Irrigation in a Tropical Environment. *Water* 8, 557.

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., and Mekonnen, M. M. (2009). Water footprint manual: State of the art 2009.

Iqbal, M. A., Eitzinger, J., Formayer, H., Hassan, A., and Heng, L. K. (2011). A simulation study for assessing yield optimization and potential for water reduction for summer-sown maize under different climate change scenarios. The Journal of Agricultural Science 149, 129-143.

Khan, A. G., Iqbal, M., and Ullah, E. (2015). Assessing the performance of different irrigation techniques to enhance the water use efficiency and yield of maize under deficit water supply. *Soil & Environment* 34.

Khan, M. A., Khan, J. A., Ali, Z., Ahmad, I., and Ahmad, M. N. (2016). The challenge of climate change and policy response in Pakistan. Environmental Earth Sciences 75, 412.

Luo, X., Xia, J., and Yang, H. (2015). Modelling water requirements of major crops and their responses to climate change in the North China Plain. Environmental Earth Sciences 74, 3531-3541.

Miao, C., Su, L., Sun, Q., and Duan, Q. (2016). A nonstationary bias-correction technique to remove bias in GCM simulations. Journal of Geophysical Research: Atmospheres 121, 5718-5735.

Mekonnen, M., and Hoekstra, A. (2010). A global and high-resolution assessment of the green, blue and grey water footprint of wheat. Hydrology and Earth System Sciences 14, 1259-1276.

Mekonnen, M. M., and Hoekstra, A. Y. (2011). The green, blue and grey water footprint of crops and derived crop products. Hydrology and Earth System Sciences 15, 1577-1600.

Paredes, P., Wei, Z., Liu, Y., Xu, D., Xin, Y., Zhang, B., and Pereira, L. S. (2015). Performance assessment of the FAO AquaCrop model for soil water, soil evaporation, biomass and yield of soybeans in North China Plain. Agricultural Water Management 152, 57-71.

Qureshi, A. S. (2011). Water Management in the Indus Basin in Pakistan: Challenges and Opportunities. Mountain Research and Development 31, 252-260.

Sun, S., Wu, P., Wang, Y., and Zhao, X. (2012). Impacts of climate change on water footprint of spring wheat production: the case of an irrigation district in China. Spanish Journal of Agricultural Research 10, 1176-1187.

Toumi, J., Er-Raki, S., Ezzahar, J., Khabba, S., Jarlan, L., and Chehbouni, A. (2016). Performance assessment of AquaCrop model for estimating evapotranspiration, soil water content and grain yield of winter wheat in Tensift Al Haouz (Morocco): Application to irrigation management. Agricultural Water Management 163, 219-235.