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**Research Review Article**

# Agricultural water use efficiency to adapt climate change in Indo-Gangetic plains of south-east Asia

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## ABSTRACT

Enhancing crop water productivity by genetic improvements or agronomic manipulations and reducing evapotranspiration losses from soil and plant surface is the need of the hour. Selection and breeding of traits which lead to increase in crop and water productivity like early maturing and stress tolerant cultivars with deep and thick root system, hairy leaves and increase in partitioning of assimilates towards grains etc. can help in increasing the water productivity. Different management options like, alteration in planting time, more water efficient planting methods, tillage practices, irrigation management, intercropping, use of anti-transpirants, row orientation, planting geometry and application of mulches and shelter belts can play important role for sustainability of water resources and crop productivity. However, the best option varies according to the location, prevailing weather conditions as well as social and economic conditions of the farmers.

**Keywords**: Climate change, Crop water productivity, Evapotranspiration, Indo-Gangetic plains, Irrigation management

Climate Change is a serious global environmental concern. The globally averaged temperature data shows a warming of 0.85°C over the period 1880–2012 and is likely to increase further by 0.3–0.7°C by 2035 (IPCC 2014). Developing countries are more vulnerable to such changes as they have limited resources to cope up with the disasters (Majumder *et al.* 2016a). Minimum temperature has been observed to increase @ 0.05°C per year in Punjab (Kingra *et al.* 2017). Climate change is severely affecting the important natural resources including water (Chatterjee *et al.* 2012) and has the potential to influence the productivity of agriculture significantly (Kingra 2016a, Kingra 2016b). Climate change might cause increased crop failure and more frequent incidences of pests (Chauhan *et al.* 2014). Changes in precipitation frequency and intensity affect run-off and the occurrence of floods and droughts (IPCC 2007). Majumder *et al.* (2016b) reported that increase in water requirements under warming scenarios will put more pressure on water resources in north-west India.

Increasing $CO_2$ increases WUE until the leaf is exposed to temperatures exceeding the optimum for growth and then WUE begins to decline (Hatfield and Donald 2019) (Table 1). Saha *et al.* (2018) reported that an increase in the temperature by 0.5, 1.0, 1.5 and 2.0°C might increase the $ET_o$ by 0.72, 1.82, 2.91 and 4.01%, respectively and water requirement of barley by 1.27, 3.10, 4.26 and 5.56% in central Punjab. Kingra and Kukal (2013) reported increase in water demand of wheat by 45mm with increase in temperature by 1°C. Effective management for water use is the only way to save water for increasing the irrigated agriculture (Boutraa 2010). Crop water requirement provide key information for irrigation scheduling, water resource planning and future decision making (Yang *et al.* 2013). Temperature, net radiation and wind speed have positive and vapour pressure has negative relation with PET (Kingra 2018). Kaur *et al.* (2018) observed positive correlation of PET of *kharif* maize with daytime temperature (r=0.76 and 0.49) and negative with relative humidity (r=-0.68 and -0.89) in central and sub-mountainous Punjab. Potential evapotranspiration (PET) of wheat is significantly affected by maximum temperature ($R^2$=0.79), rainfall ($R^2$=0.58), number of rainy days ($R^2$=0.55) and their interactive effect ($R^2$=0.83) (Kingra and Kukal 2013). Kang *et al.* (2009) reported that with temperature increasing and precipitation fluctuating, water availability and crop production will decrease in the future. Khan *et al.* (2009) reported that climate change is creating a new level of uncertainty in water governance, requiring accelerated research to avoid water-related stresses. Kingra *et al.* (2019) reported that as the water productivity of rice and wheat was negatively

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Table 1 Impact of climate change on crop water requirements and water use efficiency

| Crop/parameter | Location | Climate change factor | Impact | References |
|---|---|---|---|---|
| Maize | Madrid, Spain | RCM Projections | Increase on water requirements | Rey *et al* (2011) |
| Spring wheat | Hetao, China | Tmax, Tmin, Rain, RH, Sunshine hrs, Wind speed | Decrease in water footprint | Sun *et al.* (2012) |
| All major crops | Beijing, China | A1B, A2 and B2 climate scenarios | Significant water shortages under A1B with moderate impacts on crop production | Wang *et al.* (2013) |
| Wheat-maize rotation | Beijing, China | Irrigation management in wet, medium and dry seasons | Increase in water use efficiency | Chen *et al.* (2010) |
| Wheat, maize | Beijing, China | HadCM3 GCM Projections (Temperature, $CO_2$) | Increase in yield and water use efficiency | Guo *et al.* (2010) |
| Season-wise crop water demand | Mexico | A1B | Shortening of crop cycle, decrease in water requirement of autumn-winter and spring-summer crops and increase in perennial crops | Odeja-Bustamante *et al.* (2011) |
| Maize | Milano, Italy | A2 (Temperature, Precipitation, $CO_2$ by 2045-54) | Decrease in crop yield and increase in blue water footprint | Bocchiola *et al.* (2013) |
| Maize | Europe | A1B Scenario HaDRM3 RCM | Increase in water deficit and decrease in crop yield | Ceglar *et al.* (2013) |
| All crops | US | $CO_2$, Temperature | Increase in water use efficiency with increase in $CO_2$, decline with increase in temperature | Hatfield and Donald (2019) |
| Rice | South Korea | RCP 4.5, RCP 8.5 | Irrigation requirements decreased under RCP 4.5 and increased under RCP 8.5 due to rainfall variations | Yoon and Choi 2020 |
| Potato | South Africa | $CO_2$ and Temperature | Increase in water use efficiency with increase in $CO_2$, decline with increase in temperature | Franke *et al.* (2020) |
| Cotton | Qira Oasis, China | RCP 4.5 amd 8.5, Elevated $CO_2$ | Decrease in water requirements by 7.5-10.3% due to shorter growing season and elevated $CO_2$ | Chen *et al.* (2019) |
| Different ecosystems | China | Precipitation, $CO_2$, Temperature | Precipitation controlled WUE by 39% and $CO_2$ by 54%, warming increased water stress and evapotranspiration, $CO_2$ fertilisation compensated negative effects | Zhu *et al.* (2020 |

correlated with actual evapotranspiration, thus, by reducing the evaporation losses in the fields, there is scope for enhancing their $WP_{ET}$.

*Ways to improve water productivity*

The agricultural community has a challenge of increasing food production by more than 70% to meet demand from the global population increase by the mid-21st century (Kannan and Anandhi 2020). Climate change will affect plant growth, but we have opportunities to enhance WUE through crop selection and cultural practices to offset the impact of a changing climate (Hatfield and Donald 2019) (Table 2). The improvements in crop water productivity by genetic or agronomic manipulations is the need of the hour (Fig 1). Rani *et al.* (2017) reported that adjustments in sowing time, mulch application and need based irrigation application are effective for improving water use efficiency of maize. Some management strategies helpful in improving crop water productivity are as given below:

*Selection of improved varieties*: Ruggiero *et al.* (2017) emphasized the need for identification and characterization of key genetic and physiological processes involved in water uptake and loss. Brar *et al.* (2012) reported that cultivation of medium duration varieties of paddy during the low evaporation period can check the over draft of underground water. Similarly, hairiness increases the light reflectance and reduces water loss by increasing the boundary layer resistance (Farooq *et al.* 2009).

*Improving assimilate partitioning to grain*: Blankenagel *et al*. (2018) reported that breeding for WUE and high yield is a major challenge as the factors influencing the trait under field conditions are complex, including different scenarios of water availability. A metabolite profiling analysis of the flag leaves of 292 *indica* rice accessions has led to the identification of new molecular markers for drought tolerance and sensitivity in terms of grain yield (Melandri *et al*. 2020 and Sulpice 2020).

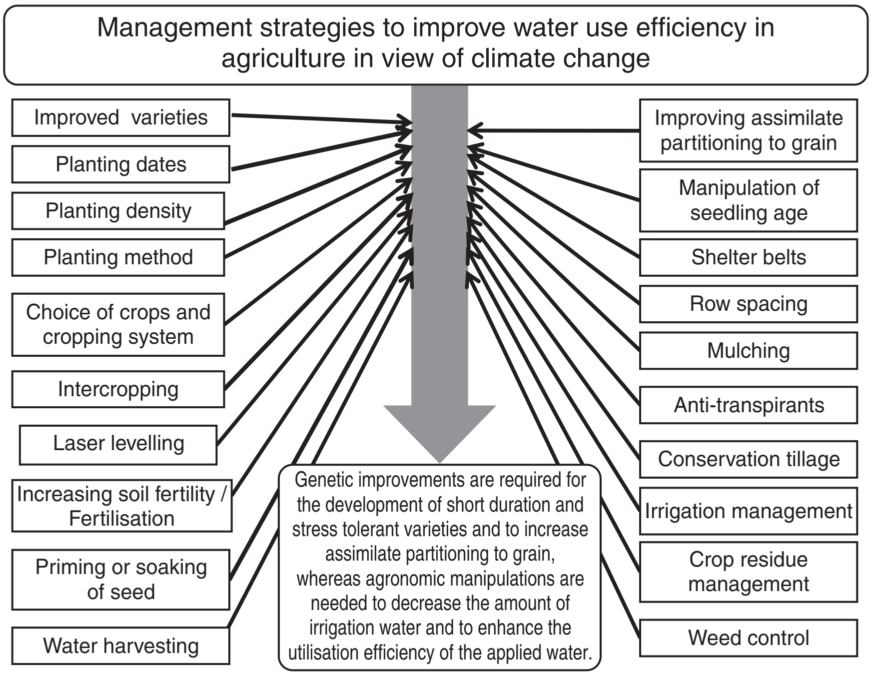
*Alteration in planting date*: Brar *et al.* (2012) also reported that delay in transplanting from June 15 to June 25 or July 5 did not show any adverse influence on yield and quality of rice, but irrigation water saving was 4.6–14.0% higher and total crop water productivity was 9.8–19.2%

Table 2 Effect of different management practices on water use efficiency of crops

| Crop | Location | Practices | Impact | References |
|---|---|---|---|---|
| Wheat | Karnal, Haryana | Hydro-priming of seed | Increase in water use efficiency | Meena *et al*. (2013) |
| | Punjab, Pakistan | Seed priming | Increase in water use efficiency | Ali *et al*. (2013) |
| | Punjab, India | Straw mulch | Decrease is soil evaporation, increase in transpiration and transpiration efficiency | Singh *et al*. (2011a) |
| | Punjab, India | Zero tillage and rice straw mulch | Increase in water use efficiency | Singh *et al*. (2011b) |
| Rice | Siruguppa, Karnataka | Age of seedlings, Modified SRI | Higher water use efficiency in young seedlings and in modified SRI | Manjunatha *et al*. (2010) |
| | Cameroon | Intermittent irrigation | 39-47% water saving, 80-100% increase in water use efficiency | Fonteh *et al*. (2013) |
| | Punjab India | Date of transplanting | Highest water use efficiency in 15 June and lowest in 5 July transplanting | Mahajan *et al*. (2000) |
| Maize | Kharagpur, India | Irrigation management | Increase in water use efficiency and net returns | Panda *et al*. (2004) |
| | Shaanxi, China | Deficit irrigation | Increase in water use efficiency | Kang *et al*. (2000) |
| Cotton, corn | Aydin, Turkey | Deficit irrigation | Increase in water use efficiency | Dagdelen *et al*. (2006) |
| Chilli pepper | Akura, Nigeria | Irrigation management | Significant effect on growth, yield and water use pattern | Akinbile and Yusoff (2011) |
| Potato | South Africa | Date of planting | Increase in yield and water use efficiency | Franke *et al.* (2020) |

higher. Kingra and Kaur (2012) reported decrease in yield and water use efficiency of *Brassica* species with delay in sowing. Singh and Kingra (2015) reported higher water productivity of 29th October and 12th November sown wheat as compared to that sown on 28th November. Franke *el al*. (2020) also recommended earlier planting of potato in South Africa to maximise yield and water use efficiency under climate change.

*Optimizing plant population and planting method*: Ali *et al.* (2013a) concluded that planting in 11 cm wide rows under conventional tillage at 100% $ET_o$ may serve as an appropriate technology for enhancing productivity of late sown wheat under limited water supplies. Chen *et al.* (2015) observed that plant growth and grain yield decreased as lateral spacing increased in wheat. Devkota *et al.* (2013) also reported significantly higher water productivity of wheat under permanent beds as compared to conventional tillage. Kingra and Mahey (2013) also observed higher evapotranspiration losses in flat than bed planting in wheat. Significantly higher leaf area and dry weight of bulbs in *kharif* onion was observed in crop raised on beds with 2.5 t/ha of crop residues compared to the rest of treatments and it recorded significantly lower fresh and dry weight of weeds/m$^2$ (Kaur 2017).



Genetic improvements are required for the development of short duration and stress tolerant varieties and to increase assimilate partitioning to grain, whereas agronomic manipulations are needed to decrease the amount of irrigation water and to enhance the utilisation efficiency of the applied water.

Fig 1 Management strategies for sustainable water management in agriculture under changing climatic conditions.

*Selection of suitable crop and cropping systems*: Yang et al. (2015) suggested that diversifying crop rotations could play an important role in mitigating the over-exploitation of the groundwater. Khan *et al.* (2005) reported higher plant height, spike length, number of grains per spike and grain yield of wheat with chickpea as intercrop. Ansari *et al.* (2011) reported that intercropping of pearl millet with pigeonpea (2:1 ratio) recorded significantly higher water use efficiency as compared to either of sole crops.

*Laser land leveling*: Laser land leveling results in water savings up to 15-30% (conserveagri.org 2009). It saved irrigation water and energy by 24% with 4.25% higher yields (Kaur *et al.* 2012). Wagan *et al.* (2015) reported about 21% of irrigation water saving with the use of laser leveling technology. Shahani *et al.* (2016) revealed about 21% irrigation water saving by the adoption of laser leveling technology alongwith higher yield and profit margins.

*Increasing soil fertility/fertilization*: Pala *et al.* (2007) concluded that nitrogen application could increase the ability of crop to utilize available water. Kundu *et al.* (2008) observed that higher dose of phosphorous increased root density and enhanced the magnitude of root water uptake. Majumder *et al.* (2016b) reported that need based irrigation scheduling in along with sub-surface manuring is helpful in managing crop water productivity under limiting water availability in north-west India.

*Mulch application*: Mulch application leads to reduction in evaporation, stabilization of temperature and improvement in the moisture status of the soil (Kingra and Kaur 2017). Ram *et al.* (2013) reported that rice straw mulch increased water use efficiency of wheat by 14-34% under different irrigation levels. Kaur and Brar (2016) reported 125.2% higher turmeric yield and 50% saving in irrigation water with mulch application @ 6 t/ha. Li *et al.* (2013) concluded that the soil moisture and temperature were improved and maize yields with plastic film, biodegradable film, maize straw were significantly increased by 13.0%, 13.8% and 15.0%. Singh *et al.* (2011) reported that retention of rice residues as surface mulch could be beneficial for moisture conservation and yield. Mulch application reduced soil evaporation during wheat growing season by 35 and 40 mm in relatively high and low rainfall years. Buttar *et al.* (2018) also reported positive impact of mulch on yield attributing characters and grain yield.

*Conservation tillage*: Su *et al.* (2007) observed no tillage and subsoil tillage with mulch to be optimum for increasing water storage, wheat yields and water use efficiency. Chakraborty *et al.* (2008) reported rice husk mulching is beneficial for wheat leading to higher grain yield and water use efficiency. Chi *et al.* (2016) reported that no-till had greater ratio of transpiration to evapotranspiration (T/ET) in bean crop.

*Seedlings planting age and seed priming*: Aslam *et al.* (2015) reported that seedling age plays an important role in yield contributing parameters leading to higher paddy yield. Chapagain and Yamaji (2010) observed synergistic effects of younger seedlings and wider spacing that led to higher productivity under system of rice intensification. Ali *et al.* (2013b) reported that the use of on-farm priming or hydro-priming of seeds for 12 h could improve grain yields in late-sown wheat. Meena *et al.* (2013) reported that priming techniques along with seeding at sub-optimal soil moisture level proved an efficient technique for enhancing water productivity of wheat (1.70 kg/m$^3$) as compared to seeding at optimum moisture level without priming (1.37 kg/m$^3$).

*Water harvesting*: The ridge furrow rainwater harvesting (RFRH) system with different ridge covering materials as mulch is a valuable technique for enhancing seed filling rates and maize productivity (Ali *et al.* 2016). Lian *et al.* (2016) also reported that ridge and furrow rainfall harvesting (RFRH) system along with appropriate fertilizer dose is effective for improving rainwater utilization, crop productivity and water use efficiency. As climate change is likely to increase rainfall variability and evaporation in future, thus rainfall harvesting may become a key intervention to cope with water scarcity (Yazar and Ali 2017).

*Irrigation management*: Butter *et al.* (2007) observed that delayed first irrigation resulted in 28% increase in seed cotton yield and 16% in stick biomass. Tang *et al.* (2010) reported that partial root zone irrigation (PRI) in cotton can substantially reduce irrigation amount. Barrios-Masias and Jackson (2016) reported that partial root zone drying (PRD) improves crop water productivity (WP), and can be applied as alternate furrow irrigation (AFI). Kusakabe *et al.* (2016) suggested that PRD can be economically beneficial for citrus growers who use double-line drip irrigation systems. Barideh *et al*. (2018) observed 28% and 32% water saving in corn with fixed partial root zone irrigation (FPRI) and alternate partial root zone irrigation (APRI), respectively, over conventional irrigation (CI). Chapagain and Yamaji (2010) observed that irrigation with alternate drying and wetting intervals (AWDI) saved 28% of water without reducing grain yield. Dejonge *et al.* (2012) also reported that due to limited water resources for agriculture crop can be intentionally stressed during specific growth stages to maximize water use efficiency.

Kaur and Brar (2016) reported 40% water saving in turmeric under drip irrigation. Qin *et al.* (2016) revealed that drip irrigation can provide adequate water and nutrition and the crop growth can be significantly enhanced. To achieve maximum WP, one, two and three irrigations (i.e., 70, 150 and 200 mm per season) were recommended for wheat in wet, medium and dry seasons, respectively (Wang *et al*. 2010). Chen *et al.* (2010) reported one, two and three irrigations for wheat in wet, medium and dry seasons, respectively, for wheat and one and two irrigations in medium and dry seasons for maize, while no irrigation was needed in wet season.

*Use of antitranspirants and shelterbelts*: Antitranspirants films increase stomatal resistance (Kettlewell *et al*. 2010). ABA induced changes constitute an improvement in water-use efficiency in greengram (Dhashnamurthi *et al.* 2014). Boari *et al.* (2016) observed that Kaolin spray increased the water use efficiency of tomato. Javan *et al.* (2013) observed significant increase in 1000-seed weight and seed yield of soybean with the spray of Kaolin, Chitosan and castorbean oil. Reduced water losses by shelterbelts can encourage early germination, plant growth and hence yield and water use efficiency. Campi *et al.* (2009) reported increase in water use efficiency of wheat within a distance of 18 times the wind break. Hana (2010) also reported significant effect of shelterbelts in conserving soil moisture.

*Weed control*: Weeds consume water intended for crops, leading to higher consumption and more evaporative water loss (Zimdahl 2013). Croissant *et al.* (2014) reported that weeds cause higher ET rates as compared to corn during its early development stage. Abouziena *et al.* (2015) also reported that proper weed control enhances available soil water for crop production.

## *Conclusion*

The study concluded that increase in heat and water stress under future climate change scenarios are likely to have adverse effects on water availability, crop yields and water productivity. Thus, there is dire need for identification and characterization of key genetic and physiological processes involved in water uptake and loss as these traits represent novel opportunities and strategies for genetic improvement of WUE and drought tolerance in crops. In addition to this, agronomic interventions such as appropriate sowing time, plant population, planting methods, fertilization, mulch application, conservation agriculture, age of seedlings, seed priming, water hearvesting and irrigation management etc. need to be adopted for judicious use of water resources to attain higher crop yield and maximize water productivity for food security.

## REFERENCES

Abouziena H F, El-Saeid H M and Amin A A E. 2015. Water losses by weeds: a review. *International Journal of Chemistry Technology Research* **7**: 323–36.

Akinbile C O and Yusoff M S. 2011. Growth, yield and water use pattern of chilli pepper under different irrigation scheduling and management. *Asian Journal of Agricultural Research* **5**(2): 154–63.

Ali H, Iqbal N, Ahmad S, Shahzad A N and Sarwar N. 2013a. Performance of late sown wheat crop under different planting geometries and irrigation regimes in arid climate. *Soil & Tillage Research* **130**: 109–19.

Ali H, Iqbal N, Shahzad A N, Sarwar N, Ahmad S and Mehmood A. 2013b. Seed priming improves irrigation water use efficiency, yield and yield components of late-sown wheat under limited water conditions. *Turkish Journal of Agriculture and Forestry* **37**: 534–44.

Ali S, Janc A, Zhang P, Khand M N, Cai T, Wei T, Ren X, Jia Q, Han Q and Jia Z. 2016. Effects of ridge-covering mulches on soil water storage and maize production under simulated rainfall in semiarid regions of China. *Agricultural Water Management* **178**: 1–11.

Ansari M A, Rana K S, Rana D S and Kumar P. 2011. Effect of nutrient management and antitranspirant on rainfed sole and intercropped pearlmillet (*Pennisetum glaucum*) and pigeonpea (*Cajanus cajan*). *Indian Journal of Agronomy* **56**: 209–16.

Aslam M M, Zeeshan M, Irum A, Hassan M U, Ali S, Hussain R, Ramzani P M A and Rashid M F. 2015. Influence of seedling age and nitrogen rates on productivity of rice (*Oryza sativa* L.): A review. *American Journal of Plant Sciences* **6**: 1361–69. http://dx.doi.org/10.4236/ajps.2015.69135

Barideh Rahman, Besharat Sina, Mohamad Morteza and Vahid Rezaverdinejad. 2018. Effects of partial root-zone irrigation on the water use efficiency and root water and nitrate uptake of corn. *Water* **10**: 526: 1–12.

Barrios-Masias F H and Jackson Louise E. 2016. Increasing the effective use of water in processing tomatoes through alternate furrow irrigation without a yield decrease. *Agricultural Water Management* **177**: 107–17.

Blankenagel S, Yang Z, Avramova V, Schon C and Grill E. 2018. Generating plants with improved water use efficiency. *Agronomy* **8:** 194. doi: 10.3390/agronomy8090194

Boari F, Dondia A, Pace B, Schittone M I and Kantore V. 2016. Kaolin improves salinity tolerance, water use efficiency and quality of tomato. *Agricultural Water Management* **167**: 29–37.

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.

Boutraa T. 2010. Improvement of water use efficiency in irrigated agriculture: A review. *Agronomy Journal* **9**: 1–8.

Brar S K, Mahal S S, Brar A S, Vashisht K K, Sharma N and Butter G S. 2012. Transplanting time and seedling age affect water productivity, rice yield and quality in north-west India. *Agricultural Water Management* **115**: 217–22.

Buttar P S, Kingra P K and Singh Som Pal. 2018. Effect of sowing dates, irrigation and mulching on growth and yield of wheat. *Agricultural Research Journal* **55**(2): 243–50.

Butter G S, Aujla M S, Thind H S, Singh C J and Saini K S. 2007. Effect of timing of first and last irrigation on the yield and water use efficiency in cotton. *Agricultural Water Management* **89**: 236–43.

Campi P, Palumbo D and Mastrorilli M. 2009. Effects of tree windbreak on microclimate and wheat productivity in a Mediterranean environment. *European Journal of Agronomy* **30**: 220–27.

Ceglar A, Chukaliev O, Duvellier G and Niemeyer S. 2013. Water requirements for maize production in Europe under changing climate conditions. *Impacts World 2013, International Conference on Climate Change Effects,* Potsdam, May 27–30.

Chapagain T and Yamaji E. 2010. The effects of irrigation method, age of seedling and spacing on crop performance, productivity and water-wise rice production in Japan. *Paddy and Water Environment* **8**: 81–90.

Chakraborty D, Nagarajan S, Aggarwal P, Gupta V K, Tomar R K, Garg R N, Sahoo R N, Sarkar A, Chopra U K, Sundara K S and Kalra N. 2008. Effect of mulching on soil and plant water status, and the growth and yield of wheat (*Triticum aestivum* L.) in a semi-arid environment. *Agricultural Water Management* **95**: 1323–34.

Chatterjee S K, Banerjee S and Bose M. 2012. Climate change impact on crop water requirement in Ganga River Basin, West Bengal, India. *3rd International Conference on Biology, Environment and Chemistry* IPCBEE vol. 46.

Chauhan B S, Kaur P, Mahajan G, Kaur R, Singh H and Kang M S. 2014. Global warming and its possible impact on agriculture in India. *Advances in Agronomy* **123**: 65–121.

Chen C, Wang E and Yu Q. 2010. Modelling the effects of climate variability and water management on crop water productivity and water balance in the North China Plain. *Agricultural Water Management* **97**: 1175–84.

Chen R, Cheng W, Cui J, Liao J, Fan H, Zheng Z and Ma F. 2015. Lateral spacing in drip-irrigated wheat: The effects on soil moisture, yield and water use efficiency. *Field Crops Research* **179**: 52–62.

Chen X, Qi Z, Gui D, Gu Z, Ma L, Zeng F and Li L. 2019. Simulating impacts oc climate change on cotton yield and water requirement using RZWQM2. *Agricultural Water Management* **222**: 231–41.

Chi J, Waldoa S, Pressleya S, O'Keeffea P, Huggins D, Stockle C, Pan W L, Brooks E and Lamb B. 2016. Assessing carbon and water dynamics of no-till and conventional tillage cropping systems in the inland Pacific Northwest US using the eddy covariance method. *Agricultural and Forest Meteorology* **218–19**: 37–49.

Croissant R L, Peterson G A and Westfall D G. 2014. Dryland Cropping Systems. http://www.ext.colostate.edu/pubs/crops/00516.html#top.

Dagdelen N, Yilmaz E, Sezgin F and Gurbaz T. 2006. Water–yield relation and water use efficiency of cotton (*Gossypium hirsutum* L.) and second crop corn (*Zea mays* L.) in western Turkey. *Agricultural Water Management* **82**: 63–85.

Dejonge K C, Ascough II J C, Andales A A, Hansen N C, Garcia L A and Arabi M. 2012. Improving evapotranspiration simulations in the CERES-Maize model under limited irrigation. *Agricultural Water Management* **115**: 92–103.

Devkota M, Martius C, Lamers J P A, Sayre K D, Devkota K P, Gupta R K, Egamberdiev O and Vlek P L G. 2013. Combining permanent beds and residue retention with nitrogen fertilization improves crop yields and water productivity in irrigated arid lands under cotton, wheat and maize. *Field Crops Research* **149**: 105–14.

Dhashnamurthi V, Sanchita V, Prashanthi R, Sathiakumar P, Srividhya S and Vijaylakhshmi C. 2014. Effects of exogenous ABA application on stomatal regulation of gas exchange parameters and calculated water use efficiency in major pulses of Tamil Nadu, India. *Indian Journal of Agricultural Research* **48**: 324–28.

Farooq M, Basra S M A, Wahid A, Khaliq A and Kobayashi N. 2009. Rice seed invigoration: a review. (In) E Lich Lichtfouse (ed). *Organic Farming, Pest Control and Remediation of Soil Pollutants*, pp 137–75. Springer, the Netherlands.

Fonteh M F, Tabi F O, Wariba A M and Zie J. 2013. Effective water management practices in irrigated rice to ensure food security and mitigate climate change in a tropical climate. *Agriculture and Biology Journal of North America* Doi: 10.525/abjna.2013.4.3.284.290

Franke A C, Muelelwa L N and Steyn J M. 2020. Impact of climate change on yield and water use efficiencies of potato in different production regions of south Africa. *South African Journal of Plant and Soil* **37**(3): 244–53.

Guo R, Lin Z, Mo X and Yang C. 2010. Responses of crop yield and water use efficiency to climate change in the North China Plain. *Agricultural Water Management* **97**: 1185–94.

Hana Kamal Osman Elshiekh. 2010. Shelter belt effects on soil temperature and moisture in the river Nile state – Sudan. Desertification and Desert Cultivation Studies Institute, University of Khartoum.

Hatfield J L and Dold C. 2019. Water-use efficiency: Advances and challenges in a changing climate. *Frontiers in Plant Science* doi: 1-.3389/fpls.2019.00103

IPCC. 2007. Climate change and water, *Technical Paper IV*.

IPCC. 2014. Climate change 2014: Impacts, adaptation, and vulnerability. Working group II contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change. Technical Report. Cambridge University Press, Cambridge, UK/New York, USA.

Javan M, Tajbakhsh M and Mandoulakani B A. 2013. Effect of antitranspirants application on yield and yield components in soybean under limited irrigation. *Journal of Applied Biological Sciences* **7**(1): 70–74.

Kang S, Shi W and Zhang J. 2000. An improved water use efficiency for maize grown under regulated deficit irrigation. *Field Crops Research* **67**: 207–14.

Kang Y, Khan S and Ma X. 2009. Climate change impacts on crop yield, crop water productivity and future security – A review. *Progress in Natural Science* **19**: 1665–74.

Kannan N and Anandhi A. 2020. Water management for sustainable food production. *Water* **12**: 778. doi: 10.3390/w12030778

Kaur A and Brar A S. 2016. Influence of mulching and irrigation scheduling on productivity and water use of turmeric (*Curcuma longa* L.) in north-western India. *Irrigation Science* doi: 10.1007/s00271-016-0501-0.

Kaur B, Singh S, Garg B R, Singh J M and Singh J. 2012. Enhancing water productivity through on-farm resource conservation technology in Punjab agriculture. *Agricultural Economics Research Review* **25**: 79–85.

Kaur Harleen, Kingra P K and Singh Som Pal. 2018. Climate variability impact on water requirement of *kharif* maize in different agroclimatic regions of Punjab. *Journal of Agrometeorology* **19** (Special Issue – AGMET 2016): 285–89.

Kaur Ramanjit. 2017. Annual Report. Division of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi.

Kettlewell P, Weerasinghe M and Grove I. 2010. Film antitranspirants to increase yield of droughted wheat. Harper Adms University.

Khan M, Khan R U, Wahab A and Rashid A. 2005. Yield and yield components of wheat as influenced by intercropping of chickpea, lentil and rapeseed in different proportions. *Pakistsn Journal of Agricultural Sciences* **42**: 3–4.

Khan S, Hanjra M A and Mu J. 2009. Water management and crop production for food security in China: A review. *Agricultural Water Management* **96**: 349–60.

Kingra P K. 2016a. Climate variability and impact on productivity of rice in central Punjab. *Journal of Agrometeorology* **18**(1): 146–48.

Kingra P K. 2016b. Climate variability impacts on wheat productivity in central Punjab. *Journal of Agrometeorology* **18**(1): 97–99.

Kingra P K. 2018. Climate variability impact on reference crop evapotranspiration computed using cropwat model. *Agricultural Research Journal* **55**(2): 265–73. DOI No. 10.5958/2395-146X.2018.00049.2

Kingra P K and Kaur P. 2012. Yield and water use efficiency of oilseed *Brassica s*pecies as influenced by irrigation levels under normal and late sown conditions in central Punjab. *Journal of Agricultural Physics* **12**(1): 1–12.

Kingra P K and Kukal S S. 2013. Impact of climate change on evapotranspiration and water productivity of wheat in central Punjab. *Journal of Research Punjab Agriculture University* **50**: 181–83.

Kingra P K, Kukal S S and Singh Som Pal. 2019. Trends in evapotranspiration and water productivity of rice and wheat in different agroclimatic regions of Punjab, India. *Journal of Agrometeorology* **21**(1): 63–69.

Kingra P K and Kaur Harleen. 2017. Microclimatic modifications to manage extreme weather vulnerability and climatic risks in crop production. *Journal of Agricultural Physics* **17**(1): 1–15.

Kingra P K and Mahey R K. 2013. Moisture extraction pattern and ET-yield models in wheat under different management practices in central Punjab. *Journal of Agrometeorology* **15**: 51-57.

Kingra P K, Setia Raj, Singh Simranjeet, Kaur Jatinder, Kaur Satinder, Singh Som Pal, Kukal S S and Pateriya Brijendra.

2017. Climatic variability and its characterization over Punjab, India. *Journal of Agrometeorology* **19**(3): 246–50.

Kusakabe A, Contreras-Barragan B A, Simpson C R, Enciso J M, Nelson S D and Melgar J C. 2016. Application of partial rootzone drying to improve irrigation water use efficiency in grape fruit trees. *Agricultural Water Management* **178**: 66–75.

Li S, Kang S Z, Zhang L, Ortega-Farias S, Li F and Du T. 2013. Measuring and modeling maize evapotranspiration under plastic film mulching condition. *Journal of Hydrology* **503**: 153–68.

Lian Y, Ali S, Zhang X, Wang T, Liu Q, Jia Q, Jia Z and Han Q. 2016. Nutrient and tillage strategies to increase grain yield and water use efficiency in semi-arid areas. *Agricultural Water Management* **178**: 137–47.

Mahajan G, Bharaj T S and Timsina J. 2000. Yield and water productivity of rice as affected by time of transplanting in Punjab, India. *Agricultural Water Management* **96**: 525–32.

Majumder D, Kingra P K and Singh S P. 2016a. Climate variability impact on water requirement of spring maize in central and sub-mountainous Punjab. *Annals of Agricultural Research* **37**: 1–6.

Majumder D, Kingra P K and Kukal S S. 2016b. Water productivity of spring maize under modified soil microenvironment. *Journal of Agrometeorology* **18(1)** : 134–36.

Meena R P, Sendhil R, Tripathi S C, Chander S, Chhokar R S and Sharma R K. 2013. Hydro-priming of seed improves the water use efficiency, grain yield and net economic return of wheat under different moisture regimes. *SAARC Journal of Agriculture* **11**: 149–59.

Melandri G, AbdElgawad H and Riewe D. 2020. Biomarkers for grain yield stability in rice under drought stress. *Journal of Experimental Botany* **71**: 669–83.

Odeja-Bustamante W, Siffuentes-Ibarra E, Iniguez-Covarrubias and Montero-Martinez M J. 2011. Climate change impact on crop development and water requirements. *Agrociencia* **45**: 1–11.

PACA. 2009. Conservation agriculture: Resource productivity and efficiency, IV World Congress on Conservation Agriculture, PACA, 1st Floor, NASC Complex, DPS Marg, Pusa, New Delhi, 2009. Available: www.conserveagri.org, 2009.

Pala M, Ryan J, Zhang H and Harris H C. 2007. Water use efficiency of wheat based rotation systems in a Mediterranean environment. *Agricultural Water Management* **93**: 136–44.

Qin S, Li S, Kang S, Du T, Tong L and Ding R. 2016. Can the drip irrigation under film mulch reduce crop evapotranspiration and save water under the sufficient irrigation condition? *Agricultural Water Management* **177**: 128–37.

Ram H, Dadhwal V, Vashist K K and Kaur H. 2013. Grain yield and water use efficiency of wheat (*Triticum aestivum* L.) in relation to irrigation levels and rice straw mulching in north-west India. *Agricultural Water Management* **128**: 92–101.

Rani Radha, Singh Som Pal and Kingra P K. 2017. Growth, yield and water-use efficiency of maize under different thermal environments, mulching and irrigation levels. *Annals of Agricultural Research New Series* **38**(1): 55-60.

Rey D, Garrido A, Minguez M I and Ruiz-Ramos M. 2011. Impact of climate change on maize's water needs, yields and profitability under various water prices in Spain. *Spanish Journal of Agricultural Research* **9**(4): 1047–58.

Ruggiero A, Punzo P, Landi S, Costa A, Oosten M J V and Grillo S. 2017. Improving plant water use efficiency through molecular genetics. *Horticulturae* **3**: 31. doi:10.3390/horticulturae3020031

Saha Sanu Kumar, Singh Som Pal and Kingra P K. 2018. Estimation of reference crop evapotranspiration of barley using CROPWAT model in Punjab. *Agricultural Research Journal* **55**(4) : 654-658. DOI No. 10.5958/2395-146X.2018.00119.9

Shahani W A, Kaiwen F and Memon A. 2016. Impact of laser leveling technology on water use efficiency and crop productivity in the cotton–wheat cropping system in Sindh. *International Journal of Research – Granthaalayah* **4**: 220–31.

Singh R K. 2010. Sensitivity of evapotranspiration to climate change: A case study of Jaipur district in Rajasthan. *Asian Man* **4**: 39–48.

Singh Sukhvir and Kingra P K. 2015. Evapotranspiration and water productivity of wheat under different hydrothermal regimes. *Agricultural Research Journal* **52**(3): 48–53. DOI No.10.5958/2395-146X.2015.00036.8

Su Z, Zhang J, Wu W, Cai D, Lv J, Jiang G, Huang J, Gao J, Hartmann R and Gabriels D. 2007. Effects of conservation tillage practices on winter wheat water-use efficiency and crop yield on Loess Plateau, China. *Agricultural Water Management* **87**: 307–14.

Sulpice R. 2020. Closing the yield gap: can metabolomics be of help? *Journal of Experimental Botany* **71**: 461–64.

Sun S K, Wu P T, Wang Y B and Zhao X N. 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**: 1176–87.

Tang L S, Li Y and Zhang J. 2010. Partial root zone irrigation increases water use efficiency, maintains yield and enhances economic profit of cotton in arid area. *Agricultural Water Management* **97**: 1527–33.

Wagan S A, Memon Q U A, Wagan T A, Memon I and Wagan Z A. 2015. Economic analysis of laser land leveling technology water use efficiency and crop productivity of wheat crop in Sindh, Pakistan. *Journal of Environment and Earth Science* (www.iiste.org) **5**(15).

Wang E, Chen C and Yu Q. 2010. Modelling the effects of climate variability and water management on crop water productivity and water balance in the North China Plain. *Agricultural Water Management* **97**: 1175–84.

Wang J, Huang J and Yan T. 2013. Impacts of climate change on water and agricultural production in ten large river basins in China. *Journal of Integrative Agriculture* **12**(7): 1267–78.

Yang X, Chen Y, Pacenka S, Gao W, Ma L, Wang G, Yan P, Sui P and Steenhuis T S. 2015. Effect of diversified crop rotations on ground water levels and crop water productivity in the North China Plain. *Journal of Hydrology* **522**: 428–38.

Yang X, Gao W, Shi Q, Chen F and Chu Q. 2013. Impact of climate change on the water requirement of summer maize in the Huang-Huai-Hai farming region. *Agricultural Water Management* **124**: 20–27.

Yazar Atilla and Ali Akhtar. 2017. *Water harvesting in dry environments.* (In) Farooq M and Siddique K (eds.). *Innovations in Dryland Agriculture*. Springer International Publishing AG2017. DOI: 10.1007/978-3-319-47928-6,3.

Yoon P R and Choi J 2020. Effects of shift in growing season due to climate change on rice yield and crop water requirements. *Paddy and Water Management* 18: 291–307.

Zhu S, Zhang C, Fang X and Cao L. 2020. Interactive and individual effects of multi-factor controls on water use efficiency in central Asian ecosystems. *Environmental Research Letters* **15.** https://doi.org/10.1088/1748-9326/ab8e8b

Zimdahl R L. 2013. *Fundamentals of Weed Science*, p 31. 4th edn, Academic Press, San Diego, California, USA.