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Climate change impacts on rice (*Oryza sativa*) productivity and strategies for its sustainable management

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ABSTRACT

Increase in climatic variations and extreme weather events in the recent past have exerted significant effect on crop productivity over different regions on earth. Such aberrations and their adverse effect on agriculture cannot be overruled in the years to come, rather it is expected to increase in future, which necessitates the need to understand their impact on crop productivity so that viable management options can be explored to sustain crop productivity and food security in future. Rice (*Oryza sativa* L.) is the most important staple food for about 150 million people worldwide, especially in east and south Asia, the middle east, Latin America and the West Indies. It is a tropical crop and is thus adapted to warm and humid conditions. Tropical and sub-tropical areas are at, a greater risk as the prevailing temperatures are already on higher side in these areas and the crops are therefore exposed to warmer limits. Thus, in warm areas of the world, future global warming may result in substantial yield decrease because of the sensitivity of flowering and seed set to high temperatures and the possibility of water shortage that may result from increased evapotranspiration. Warming conditions may lead to reduction in crop duration and increase in respiratory losses, thus decreasing net photosynthesis and crop productivity. Although increase in CO_2 levels lead to positive growth response, this effect is nullified due to increase in temperature. Increase in CO_2 concentration can counterbalance the effect of increase in temperature by 1–2°C but further warming will have negative impact on rice productivity even under elevated CO_2 levels. To overcome the adverse effects of climate change on rice productivity, agronomic management practices like cultivation system, irrigation management and fertilizer management etc. can play a significant role either by leading to reduction in greenhouse gas (GHG) emission or by reduction of climate change impact on rice productivity. In addition to this, various breeding techniques like screening for stress tolerance, conventional breeding techniques as well as molecular and biotechnological strategies need to be incorporated for developing varieties tolerant to various stresses.

Key words: Climate change, Global warming, Greenhouse gases, Rice.

Climate is the average pattern of weather for a particular place over several decades. Climate change refers to long term changes in weather, including changes in temperature, wind pattern and rainfall, especially the increase in temperature of earth's atmosphere, which is caused by increase in the concentration of greenhouse gases (GHGs) particularly carbon dioxide. Increasing concentration of CO_2 and other green house gases has resulted in 0.85°C rise in global average temperature over past 100 years. The Inter-governmental Panel on Climate Change (IPCC 2014) has predicted a rise in global surface temperature within the range of 0.4 to 2.6°C by 2056-2065 and 0.3-4.8°C by 2081-2100 relative to the reference period of 1986-2005. The climate change, especially the global warming occurring over the entire earth, has started affecting agricultural productivity to a great extent. Accumulation of greenhouse gases in the atmosphere has exposed us to the potential warming and its adverse effects on agriculture (Haris *et al.* 2013).

Changes in the frequency and intensity of precipitation directly affect the magnitude and timing of runoff and the intensity of floods and droughts (IPCC 2007). The increased frequency of extreme weather events has started creating imbalances in the hydrological cycle and is resulting in large year-to-year fluctuations in crop yields and water productivity in the recent years. Increased concentration of greenhouse gases especially CO_2 has a direct impact on crop growth and productivity. Under elevated CO_2 conditions, the stomatal conductance in most species decreases, which may result in lower transpiration per unit leaf area. The partial closure of stomata is reflected in the reduced conductance at the leaf level. The combined effects of CO_2 on evapotranspiration are generally modest, between

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a reduction of few per cent for short crops to about 15% for tall, rough vegetation (Kruijt *et al.* 2008).

Agriculture has always been vulnerable to unfavorable weather events and climate change. Climate is one of the most important input factors for agricultural productivity all over the world. According to International Food Policy Research Institute's (IFPRI) report on climate change: impact on agriculture and cost of adaptation, rice prices will increase between 32 to 37% by 2050 as a result of climate change. They also reported that yield losses in rice could be between 10-15%. Thus, global warming and climatic changes will have adverse impacts on rice productivity in the region, in the coming years. Tropical and sub-tropical areas are at higher risk as the prevailing temperature are already on higher side in these areas and the crops are already exposed to warmer limits. Hence, further warming in these areas will have severe negative impacts on crop productivity.

Rice (*Oryza sativa* L.) is the most important staple food for about 150 million people of the world especially, in east and south Asia, the middle east, Latin America and the West Indies. Rice is a predominant crop of north-west India including Punjab. During 2013-14 it was grown on 43.9 m ha in India with average yield of 36.3 q/ha and production of 159.45 million tonnes, whereas in Punjab it was grown on 2.85 m ha with average yield of 59.3 q/ha and production of 16.9 million tonnes. Punjab covering only 1.54% of the geographical area of India, produces 10% rice of the country and contributes nearly 28% of rice to the central pool of foodgrains (Anonymous 2015). But large oscillations have been observed in rice productivity in recent years because of fluctuations in climatic conditions in the region. In tropical regions like Punjab, high temperature is already one of the major environmental stresses limiting the productivity of rice crop, because of reduction in grain filling duration, grain weight and quality of the produce.

The effects of high-temperature stress on the continuum of soil–rice plant–atmosphere for different ecologies (upland and in lowland rice areas) also need detailed investigations. Most agronomic interventions for the management of high-temperature stress aim at early sowing of rice cultivars or selection of early maturing cultivars to avoid high temperatures during grain filling. But these measures are not sufficient as high-temperature stress events will* become more frequent and severe in the coming years. Developing high-temperature stress tolerant rice cultivars has become a proposed alternative, but requires a complete understanding of genetics, biochemical and physiological processes for identifying and selecting traits, and enhancing tolerance mechanisms in rice cultivars (Krishnan *et al.* 2011).

Thus, there is a need to understand the influence of climate change on rice productivity, so that suitable adaptation/mitigation strategies can be explored to sustain agricultural productivity and food security under future warmer climatic conditions. Therefore, recent studies on climate change, its effect on rice productivity and various adaptation/mitigation strategies were collected from different journals and websites. Based on the review and analysis of relevant literature, an overview of recent climatic changes and their effect on rice productivity has been discussed in the present manuscript. An attempt has also been made to identify and discuss various adaptation/mitigation strategies to manage the climate change impact on rice productivity.

Climatic requirements of rice

Rice is a tropical crop and is thus adapted to warm and humid conditions. It is a heat loving plant and requires high temperature for its growth and development. It is best suited to the regions with high temperature, high humidity, prolonged sunshine hours and assured water supply. A temperature range of 20-37.5°C is required for its optimum growth. The crop requires higher temperature at tillering than that during early growth. The temperature requirement for blossoming ranges between 26.5 and 29.5°C (Anonymous 2015a). Minimum, optimum and maximum cardinal temperature for germination of rice is 10-12, 30-32 and 36-38°C, respectively. It requires average temperature of 22°C for its growth. Minimum, optimum and maximum cardinal temperatures for rice are 15-20, 30-38 and 45-50°C. Temperatures below 14°C and above 38°C induce sterility in rice (Reddy and Reddy 2007). However, it can tolerate temperature upto 40°C if water is not limiting. But if night temperature drops lower than 15°C during the entire vegetative phase, the rice yield is greatly reduced due to the formation of sterile spikelets, which are induced by low temperature. The period of 10-14 days before heading is most critical for low temperature (Pillai and Nair 2010). However, optimum temperature for rice varies with its growth stages. Rice requires optimum temperature of 20-25°C for germination, 25-30°C for seedling establishment, 31°C for tillering, 33°C for panicle initiation, 30-32°C for anthesis and 20-25°C for ripening (Balasubramanian and Palaniappan 2001, Went 2006). Higher day and night temperature has adverse effect on rice productivity due to spikelet sterility and enhanced maturity (Venkataramanan and Singh 2009, Mohammed and Tarpley 2009).

Thus, in warm areas of the world, future global warming may result in substantial yield decrease because of the sensitivity of flowering and seed set to high temperatures and the possibility of water shortage that may result from increased evapotranspiration. Although, vegetative growth in rice continues with day time temperature as high as 40°C, development of florets is extremely sensitive to temperature higher than 35°C. The effect of night time temperature stress is even more adverse than day. High temperature or heat stress results in deprived anther dehiscence, impaired pollination and abnormal pollen germination that cause floret sterility. This decrease in pollen viability is presumably caused by imbalance in protein expression, abandoned biosynthesis, partitioning and translocation of soluble sugars, imbalance in phytohormone release, and loss of pollen water content. Rice responds to heat stress by adjusting various physiochemical mechanisms, viz. growth inhibition, leaf senescence and alteration in basic physiological processes. Antioxidant enzymes, calcium and iron also play an important role in managing heat stress. Response of rice to heat stress varies with plant ecotype, growth stage, heat intensity and time of stress application (Shah *et al.* 2018). High temperature stress can be managed by developing heat-tolerant genotypes. Rice breeding and screening may be based on anther dehiscence, pollen tube development and pollen germination on stigma.

Effect of climate change on rice productivity

The increase in both frequency and intensity of high temperature, besides its large variability will result in up to 40% yield reduction in rice by the end of 21st century (Fahad *et al.* 2018). Large year-to-year variations in rice productivity are being observed over different regions of the globe. Recent climatic variability conditions have also witnessed large oscillations in rice productivity under central Punjab conditions. In view of the changing climatic conditions, large yield losses have been predicted due to warming scenarios in future. It has been predicted that irrigated rice yield will decrease by 10–15% sleaving >25 million children malnourished. According to International Food Policy Research Institute (IFPRI), Climate change will also result in increase in price of rice by 12%, wheat by 90% and maize by 35% by the year 2050. Danvi *et al.* (2018) conducted the simulation studies based on the traditional and the rainfed-bunded rice cultivation systems and analyzed up to the year 2049 with a special focus on the period of 2030–2049. Compared to land use, climate change impact on hydrological processes was overwhelming at all watersheds. The watersheds with a high portion of cultivated areas are more sensitive to changes in climate resulting in a decrease of water yield of up to 50% (145 mm). Bunded fields cause a rise in surface runoff projected to be up to 28% (18 mm) in their lowlands, while processes were insignificantly affected at the vegetation dominated-watershed. Analyzing three watersheds instead of one as is usually done provides further insight into the natural variability band therefore gives more evidence of possible future processes and management strategies.

Effect of temperature: Although rice crop is adapted to warmer conditions, in the tropical and sub-tropical areas including Indian sub-continent it is already exposed to high temperature conditions. Thus, further warming is expected to have adverse effects on rice productivity especially in these regions. Overall, temperature increases are predicted to reduce rice yields. An increase of 2-4^{o}C is predicted to result in reduction in rice productivity under Indian conditions. Sinha and Swaminathan (1991) reported that increase in temperature by 2^{o}C could decrease rice productivity by about 0.75 t/ha in the high yielding areas. Peng *et al.* (2004) reported 10% decline in grain yield of rice with 1^{o}C increase in minimum temperature. Although additional CO_2 can benefit the crop, this effect will be nullified by increase in temperature. Warming scenario reduces productivity mainly due to its effect on crop phenology. Enhanced crop maturity due to warming has adverse effect on rice yields. Mahi (1996) reported that leaf area index of rice reduced by 17.8 to 24.3%, biomass production by 12.6 to 19.9% and grain yield by 14.2 to 26.2% below normal with increasing temperatures up to 2.5^{o}C above normal. Jalota *et al.* (2014) have reported reduction in rice growing period by 17-23 days by mid century and by 25-30 by end century over different locations in Punjab in view of futuristic warming scenarios.

Mathauda *et al.* (2000) reported decrease in grain yield, number of grains per ear, maximum leaf area index and straw yield of rice by 8.4, 12.4, 3.9 and 6.4%, respectively due to warming by 2^{o}C under Punjab conditions. Kaur and Hundal (2010) also reported enhancement in heading and maturity of rice by 4 and 8 days, respectively, with increase in minimum temperature. The study depicted increase in grain yield, biomass yield and maximum leaf area index of rice by 27%, 20% and 8% due to decrease in temperature by 3^{o}C from normal, whereas increase in temperature by 3^{o}C than normal decreased grain yield, biomass yield and maximum leaf area index by 10, 6 and 12%, respectively under Punjab conditions. Rani *et al.* (2011) reported significant decrease in rice productivity under warming scenarios. The productivity decreased drastically when warming increased from 1-4^{o}C. Nyang *et al.* (2014) also reported significant reduction in grain yield of rice with increase in maximum as well as minimum temperature.

Venkatramanan and Singh (2009) conducted a control study on two rice cultivars (Pusa Sugandh -2 and Pusa 44) and reported that high day and night temperature resulted in less rice productivity. High day and night temperature treatments greatly reduce the tiller production and their development. Reduction in number of tillers was due to mortality of tillers. High temperature caused early flowering and maturity which results in reduction in grain filling period. Due to shorter grain filling period, grains are of smaller size and this causes reduction in yield. The panicle dry weight declined drastically in all the plants subjected to high temperature because of spikelet sterility. Mohammed and Tarpley (2009) also found that coincidence of high day and night time temperature with critical development stages such as flowering, there is improper pollination and a reduction in number of pollen germinated on the stigma, which ultimately leads to spikelet sterility.

Singh *et al.* (2010) reported that rise in temperature causes detrimental effects on growth, yield and quality of the rice by affecting its phenology, physiology and yield components. The unusual rise in temperature during different growth phases adversely affebncts rice growth and productivity. High temperature (+2.5^{o}C) during vegetative and reproductive growth phases causes greater and almost equal reduction in biomass (23% and 26%) and grain yield (23% and 27%) as compared to that during the ripening growth phase which showed 8% and 7% reduction in biomass and grain yield, respectively. The marked reduction in grain yield of rice under high temperature stress during vegetative and reproductive growth was mainly attributed to the significant reduction in the number of panicles/m^2 and number of grains/panicle. However, the relatively low reduction in grain yield (8%) due to heat stress during ripening phase was probably caused by the small reduction in 1000-grain weight and the number of grains/panicle.

Chakrabarti *et al.* (2010) reported that increased temperature due to global warming may reduce pollen germination and induce spikelet sterility in rice crop. Anthesis was observed as the most sensitive stage to high temperature, as higher temperature during this stage might cause reduction in floral reproduction. Matsui *et al.* (2000) reported that rise in temperature increased pollen sterility and reduced germination of pollen grains on the stigma. Heading and flowering appeared to be the most sensitive stages of rice affected by high temperature. At flowering, it inhibits the swelling of pollen grains, which is the major driving force behind anther dehiscence. Grain yield of rice declined by an average of 7-8% per 1°C rise in temperature when day time temperature varied between 28°C and 34°C. Non-basmati varieties were less affected by increased temperature than basmati varieties. The study indicated that increased temperature limit the rice yield by affecting pollen germination and grain formation. Rowhani *et al.* (2011) also reported that seasonal temperature increases have the most important impacts on crop yields. Seasonal temperature increase by 2°C reduces average rice yield by 7.6%.

Extreme temperature impacts on field crop are of key concern and increasingly assessed, however the studies have seldom taken into account the automatic adaptations such as shifts in planting dates, phenological dynamics and cultivars. Zhang *et al.* (2016) studied the trial data on rice phenology, agro-meteorological hazards and yields during 1981–2009 at 120 national agro-meteorological experiment stations. The detailed data provide us a unique opportunity to quantify extreme temperature impacts on rice yield more precisely and in a setting with automatic adaptations. In this study, changes in an accumulated thermal index (growing degree day, GDD), a high temperature stress index (>35◦C high temperature degree day, HDD), and a cold stress index (<20◦C cold degree day, CDD), were firstl investigated. Then, their impacts on rice yield were further quantified by multivariable analysis. The results showed that in the past three decades, for early rice, late rice and single rice in western part, and single rice in other parts of the middle and lower reaches of Yangtze River, respectively, rice yield increased by 5.83%, 1.71%,8.73% and 3.49% due to increase in GDD. Rice yield was observed to be more sensitive to high temperature stress than to cold temperature stress. It decreased by 0.14%, 0.32%, 0.34% and 0.14% due to increase in HDD, in contrast increased by 1.61%, 0.26%, 0.16% and 0.01% due to decrease in CDD. In addition, decreases in solar radiation reduced rice yield by 0.96%, 0.13%, 9.34% and 6.02%. In the past three decades, the positive impacts of increase in GDD and the negative impacts of decrease in solar radiation played dominant roles in determining overall climate impacts on yield. However, with climate warming in future, the positive impacts of increase in GDD and decrease in CDD will be offset by increase in HDD, resulting in overall negative climate impacts on yield.

Effect of CO_2: Baker *et al.* (1990) reported increase in mean biomass, leaf area duration, grain yield, number of panicles/plant, number of filled grains/plant, 1000-grain weight and net assimilation rate with increase in CO_2 concentration. Uprety *et al.* (2003) also reported increase in tiller number, plant height and leaf number of rice cultivars Pusa Basmati 1 and Pusa 677 under elevated CO_2 conditions. The study depicted that elevated CO_2 decreased dark respiration rate, stomatal conductance and increased net photosynthetic rate in rice. De Costa *et al.* (2006) reported significant increase in number of grains/m^2, percent filled grains, grain weight, grain yield and harvest index of rice under elevated CO_2 conditions. Hundal and Kaur (2007) reported increase in maximum leaf area index, biomass and grain yield of rice by 11, 9 and 10% under elevated CO_2 concentration of 600 ppm. Singh *et al.* (2013) reported higher leaf area index of rice under 480 ppm CO_2 as compared to 380 ppm during the entire growing period of rice. Rani *et al.* (2011) reported significant increase in rice productivity with increase in CO_2 concentration from 340 ppm (7.62 t/ha) to 640 ppm (9.00 t/ha).

Interactive effect of temperature and CO_2 : Although crop productivity is increased with increase in CO_2 concentration, its effect is nullified due to increase in temperature. Basak *et al.* (2010) reported that increase in incoming solar radiation and CO_2 concentration were found to increase rice yield, but their effect was not significant as compared to the negative effects of temperature. Rani *et al.* (2011) reported that the yield of rice increased with increase in CO_2 concentration, however, decrease in yield was noticed with increase in temperature at existing CO_2 level. Nyang *et al.* (2014) revealed that increase in both maximum and minimum temperature affects Basmati 370 grain yield under SRI. Increase in CO_2 concentration leads to increase in grain yield for Basmati 370 under SRI. Increase in solar radiation also had an increasing impact on Basmati 370 grain yield. Further research is warranted on the interaction of CO_2 and temperature at both vegetative and reproductive stages, paving ways for harnessing the benefits of increasing CO_2 for higher yields.

Effect of solar radiation: Solar radiation is the ultimate source of energy for the synthesis of carbohydrates necessary for plant growth and development. Solar radiation falling in the narrow wavelength range of 400-700 nm, known as photosynthetically active radiation or light, is used by plants in the process of photosynthesis. Light is essential for photosynthesis. It governs the distribution of photosynthates and affects the production of tillers and yield. Majority of plants flower only when they are exposed to specific day length which is called as photoperiod (Dhaliwal and Kler 1995). Low sunshine hours during reproductive period lead to significant reduction in crop yield. For getting higher yield, solar radiation of 300 cal/m^2/day is required. A combination of low daily mean temperature and high solar radiation during reproductive phase is favourable for getting higher yield (Pillai and Nair 2010). Mahi (1996) reported that leaf area index of rice reduced by 4.5 to 7.8% and grain yield by 1.2 to 11.1% from normal, when solar radiation decreased up to 10% below normal. Kumar and Kumari (2002) revealed significant influence of solar radiation on productivity of upland rice. Maximum grain yield was revealed under open conditions, but a significant reduction in grain yield was observed with increase in shade level as grain yield reduced by 41 to 80% at 20 and 40% shade level. Kropff *et al.* (2003) also reported significant decline in rice productivity with decrease in solar radiation.

Quality, intensity and duration are most important in light. Maximum photosynthesis occurs in red and blue light whereas green light is reflected by plants. With increase in light intensity photosynthesis increases but only up to a point called as light compensation point where photosynthesis is equal to respiration after that no increase in photosynthesis occurs even if light intensity increases. According to duration of light and dark periods, there are short day plants, long day plants, intermediate plants and day neutral plants. Rice requires long day during vegetative growth and short days during flowering. It requires ≤10 hours daylight during flowering and >300 sunshine hours, 45 days before harvest results in high grain yield (Pandey and Sinha 2006). Saturation light intensity (light intensity at which maximum photosynthesis occurs) for rice is 5000-6000 ft.c. (Gill 2000 and Srivastava 2006). Low solar radiations at reproductive stage significantly reduce the yield by affecting spikelet numbers and development. The grain weight per spike can be improved if the solar radiations are optimum during maturity. Singh (2005) reported that solar radiation has a profound effect on crop growth and productivity. Low light stress caused a significant increase in spikelet sterility. Maximum yield was observed under normal light whereas minimum yield was found when light was 40% at all the growth stages. Yadav *et al.* (2015) also reported increase in rice productivity with increase in solar radiation.

Effect of moisture/rainfall: Rice crop has high moisture requirement. It requires about 1240 mm of rainfall during its growing period (Rao *et al.* 2010). However, the humidity needs vary according to the variety. For early types, the favourable range is 83-85% and for late ones, it is 67-68% (Anonymous 2015a). Flowering is inhibited when relative humidity is <40% and is best at 70-80% relative humidity. Land submergence up to milking stage is ideal for optimum yield. Soil moisture stress from flowering to milk stage leads to highest reduction (around 75%) in grain yield. Water stress results in low leaf water potential which reduces the translocation of photosynthates in plants. Moist/humid weather during vegetative growth and dry/sunny weather during ripening is most desirable. When water stress occurs before panicle initiation it results in reduced number of spikelets. High humidity at the time of ripening favours occurrence of diseases. Continuous rain at the time of flowering causes poor fertilization, grain formation and grain filling leading to reduction in yield (Reddy and Reddy 2009).

Sarvestani *et al* (2008) observed that water stress at any stage can reduce the yield of rice. Water deficit during vegetative, flowering and grain filling stages reduced the mean grain yield by 21%, 50% and 21% respectively in comparison to control. Water stress at vegetative growth reduced the total biomass due to decrease in photosynthetic rate and dry matter accumulation, which reduced plant height and tiller number. At reproductive stage, it reduced the grain filling duration, grain weight and grain number. At flowering stage, it reduced the grain yield by affecting pollination and fertilization. At grain filling, it reduced the grain weight which results in reduction in yield of rice crop. Maximum reduction (50%) was observed when moisture stress occured at reproductive stage. Ali *et al.* (2005) observed that plant height, number of grains and grain yield reduced and sterility percentage was increased due to low moisture conditions. This study shows reduction in all the yield components, i.e. plant height, panicle length, number of productive tillers and 1000-grain weight which caused reduction in grain yield.

Management strategies

The mitigation potential of rice production to climate change lies more on its capabilities for soil carbon sequestration; there exists strong synergies with sustainable agriculture. This can reduce vulnerability to high-temperature stress effects in the long run. Another vital aspect of mitigation potential is related to the reduction of CH_4 emission as nearly 50% of rice is cultivated under submerged conditions and human control over the rates of emission from rice fields can be manipulated effectively with different cultivation methods and use of inputs. Tropical regions provide opportunities for about 65% of the total mitigation potential for climate change, which includes higher temperature stress because more reduction in emission of greenhouse gas methane from rice fields can be achieved. Thus, rice productivity is expected to be adversely affected by climatic changes and adaptation measures need to be adopted to manage the climate variability impact to sustain crop productivity and ensure food security in future. Different management strategies that either lead to reduction in greenhouse gas emission or reduction of climate change impact on rice productivity are depicted in Fig 1.

Date of planting/transplanting: Change in planting/transplanting date leads to improvement of yield and water use efficiency by growing crops during the period of least evaporative demand for which yield potential is high. In north-west India, ET requirement of rice declines from around 800 – 550 mm as the date of transplanting is delayed from 1 May to 30 June without compromising rice yield. Kaur *et al.* (2014) also observed higher PAR interception in early transplanted (15 June) crop leading to higher grain yield of rice. However, Mahajan *et al.* (2009) concluded that substantial amount of water can be saved and yield increased by transplanting short-duration cultivars during the period of peak evaporative demand, or water saved and yield maintained by transplanting a photoperiod-sensitive cultivar late in the season when the evaporative demand is

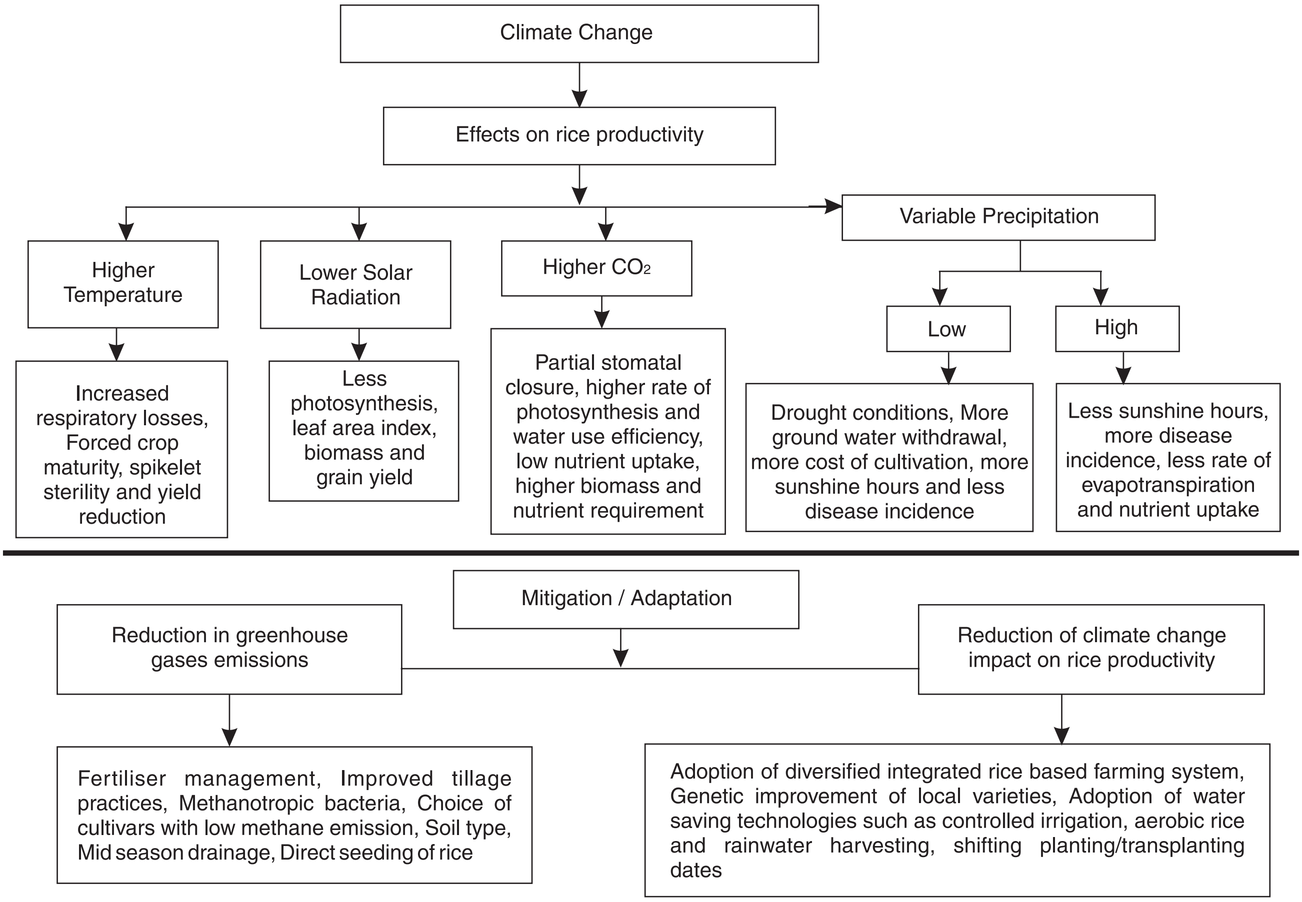

Fig 1 Climate change effects on rice productivity and its mitigation/adaptation strategies

low. Jalota *et al.* (2014) also reported delay in transplanting of rice by 15 days as the best adaptation measure to sustain its productivity under Punjab conditions.

Cultivation systems: Alberto *et al.* (2009) observed that aerobic rice fields had higher sensible heat flux, lower latent heat flux and consequently higher Bowen ratio than flooded fields indicating that a large proportion of the available net radiation was used as sensible heat transfer for warming the surrounding air. The total carbon budget integrated over the cropping period showed that the net ecosystem exchange (NEE) in the flooded rice fields was about three times higher than in aerobic fields, while gross primary production (GPP) and ecosystem respiration (Re) were 1.5 and 1.2 times higher, respectively. The ratio of Re/GPP for flooded fields was 0.67, while it was 0.83 for aerobic rice fields. Geethalakshmi *et al.* (2011) reported that System for Rice Intensification (SRI) produced highest grain yield and water use efficiency. They also suggested the use of temperature tolerant varieties and green manures/ biofertilisers for economizing water and increasing rice productivity under warmer climate. A tremendously high. yield of 19 t/ha has been reported by China in SRI. In India too, exceptionally high yields (50-100%) have been reported because of the various reasons as cited by different scientists include: planting of young seedlings (~12 days old) leading to profuse tillering, prolific root system and strong stem with larger and heavy panicles resulting from wider spacing, better soil moisture and aeration regimes leading to better root respiration, nutrient availability and uptake, use of organic manures improving soil fertility, cono-weeding modifying soil environment (Dass *et al.* 2015). Sam (2015) concluded SRI as a climate smart method for increasing rice productivity by improving the management of soil, water, nutrients and weeds as it combines a set of best practices that can increase rice yield on poor soils up to 15 tonnes/ha, reduce irrigation water requirements, and use only local inputs (Stoop *et al.* 2002, Uphoff 2007, Kassam *et al.* 2011).

Water management: Alternate wetting and drying is an effective strategy for reducing water use, mitigating green house gas emission and increasing net returns of farmers. Pathak *et al.* (2003) observed that continuously saturated soil in rice gave higher methane emission as compared to intermittent wetting and drying, but the yields were lower. Intermittent wetting and drying in rice seemed to have potential to reduce the methane emission. Fonteh *et al.* (2013) reported that intermittent wetting at 3 cm water depth resulted in highest crop productivity as compared to continuous flooding at 3 cm water depth and intermittent wetting at 5 and 7 cm water depth. Rezaei (2013) also reported higher straw weight and harvest index in alternate wetting and drying as compared to flood irrigation. They also proposed mixing fresh and saline water and intermittent irrigation as effective measures in the management of salinity and water stress in rice.

Fertiliser management: Bharati *et al.* (2000) studied that dual cropping of *Azolla* in conjunction with urea considerably reduced CH_4 efflux without affecting the rice yield and can be used as practical mitigation option for minimizing CH_4 flux from flooded fields. Pathak *et al.* (2003) reported that application of dicycandiamide (DCD) with urea reduced the emission of CH_4 in rice-wheat system to 70%, while substituting 50% of inorganic nitrogen with farm yard manure increased emission to 172% as compared to the application of entire amount of nitrogen through urea. In the most common fertiliser practices in the Indo-Gangetic Plains, the emission of CH_4 was 21.1 kg/ha.

Crop simulation modelling: Crop simulation modelling is another very effective tool for assessing the impact of climatic variations and exploring viable strategies for their management in agriculture. Process-based models of crop growth and development are integral parts of the most effective decision support system (DSS) models and have been developed and used for more than 40 years (Basso and Ritchie 2015). Crop models can be used to understand the effects of climatie changes such as elevated carbondioxide, changes in temperature and rainfall on crop development, growth and yield (Pal *et al.* 2014, Rauff and Bello 2015). These can be specially beneficial in the developing countries where infrastructural and financial constraints limit exhaustive experimental research under controlled environments. These models are capable of providing useful information for exploring combinations of management strategies to reach the multiple goals required for sustainable crop production. A specific strength of these crop models lies in their ability to quantify variability of crop performance due to variability in seasonal weather conditions and to predict the long-term impacts of climate change and land use options (Timsina and Humphreys 2006, Liu *et al*, 2010). CERES-rice model is able to predict quite accurately rice yield using the extended range weather forecast (Ghosh *et al.* 2014).

Breeding techniques

Screening for stress tolerance: Different studies conducted by various researchers clearly show the presence of genetic variability among rice cultivars for tolerance to high-temperature stress, which needs to be explored in the breeding programs. Although the genus *Oryza* has a pan-tropical distribution, the geographic origin of rice cultivars is not related to susceptibility to heat stress. A rice genotype for example, BKN6624-46-2, a selection from Thailand, is more susceptible to high temperatures at the vegetative and anthesis stages than the Japanese genotype Fujisaka 5. Many important questions relating to selection of germplasm and exploitation of biodiversity to maximize crop yield remain unanswered. At present, efforts are sporadic on the genetic improvement of rice for high-temperature stress, and the lack of full understanding of how rice plants cope up with high-temperature stress is the main reason for such weak efforts (Singla *et al.* 1997). The conservation of rice germplasm and its use in many breeding programs provide many opportunities for evaluation of different germplasm for resistance to high-temperature stress. Wild species, obsolete cultivars, minor varieties, or types of rice are the promising sources harboring genes controlling high-temperature stress tolerance.

In addition to this, other sources of genes, which include microorganisms, can also be used and exploited for genetic studies. The latest and innovative biotechnological methods and approaches will help to harness the variations efficiently and to incorporate traits for temperature stress tolerance. Genotypes for flowering and grain filling which are sensitive to high temperature stress and directly related to yield have been identified (Oh-e *et al.* 2007, Prasad *et al.* 2006). The systematic evaluation for high-temperature stress tolerance is a costly and time-consuming process. It requires well-defined screening and selection procedures (Singh *et al.* 2007). Several putative traits might affect the response of rice plants to high-temperature stress. In the target environment, only a few traits contribute to yield. Hence, selection of physiological traits is of paramount importance. Only those traits of known value when combined with selection for yield per se can help to achieve the breeding objectives, either in parental selection or in the screening of segregating material.

Conventional breeding strategies

Conventional breeding methods have depended mainly on the performance of rice such as potential yield of rice crop or some other traits which are highly and closely associated with yield under stress conditions as a selection criterion. This approach can help to identify cultivars which perform better with improved adaptation under stress conditions, but advancement has been slow on genotype-environmental interactions because of year-to-year variations in the timing and intensity of high temperature stress under natural field conditions. Attempts to develop heat-tolerant genotypes via conventional plant breeding protocols are successful and both avoidance and tolerance to heat stress at anthesis are useful traits for breeding programs for hotter rice-growing environments, now as well as in the future (IRRI 2007).

Molecular and biotechnological strategies

The most recent and innovative technologies such as molecular mapping and biotechnological strategies offer opportunities to gather information on major genes and quantitative trait loci underlying heat stress tolerance. Even though the most important problem with temperature tolerance in rice is pollen (from production to pollination), there are different studies that report heat stress tolerance associated with many different morphological and physiological traits or responses of leaves, stems, reproductive organs and roots. These responses may be controlled by multiple genes. Presently, there is a limited understanding of the nature of quantitative trait loci for heat tolerance (Huang *et al.* 2008), which needs to be explored in view of warming scenarios in future.

Conclusion

The study reveals that warming conditions will lead to reduction in crop duration and increase in respiratory losses, thus decreasing net photosynthesis and ultimately crop productivity. Although increase in CO_2 levels lead to positive growth response, but this effect is nullified due to increase in temperature. However, increase in CO_2 concentration can counterbalance the effect of increase in temperature by 1-2^{o}C and further warming will have negative impact of rice productivity even under elevated CO_2 levels. Hence, to overcome the adverse effects of climate change on rice productivity, integration of agronomic and breeding approaches can play a significant role. Impact of climate change can be reduced by the adoption of diversified integrated rice based farming system, adoption of water saving technologies such as direct sowing of rice, irrigation management, rainwater harvesting etc. In addition to this, methane emission can be reduced by tillage practices, soil type, rice cultivar and water management. Along with various agronomic interventions, breeding approaches to locate/identify the genes responsible for high temperature stress tolerance will act as boon for harnessing higher rice productivity in the upcoming warmer climatic conditions.

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