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Strategies for Boosting Rice Yield in the Face of Climate Change in India

Bhagirath Singh Chauhan[1]* and Gulshan Mahajan[2]

[1]*Weed Scientist, International Rice Research Institute, Philippines*
[2]*Rice Agronomist, Punjab Agricultural University, India*

Abstract

Rice (Oryza sativa L.) is an important staple crop in Asia, including India. During the era of the Green Revolution, the rate of growth in rice production was higher than the population growth and thus production was in the surplus. But now, with climate change, production and productivity gains of rice are a question mark. Rice contributes to global climate change through the emission of greenhouse gases, such as methane and nitrous oxide, which are responsible for global warming, and, in turn, suffers the consequences of climate change. To cope with the anticipated impact of this change, mitigation and adaptation strategies need to be evaluated. Mitigation of the causal factors and adaptation of the crop to changing climate are two broad strategies to restrain and cope with the changing climate; mitigation strategies aim at reducing the emission of greenhouse gases into the atmosphere, whereas the adaptation strategies aims at enabling the plant to perform optimally under adverse climatic conditions through cultural and genetic approaches.

Keywords: Greenhouse gases; Cultural strategies; Genetic strategies

Introduction

Rice is the most important staple crop and more than half of the world population dependent on rice. The slogan "rice is life" is very much appropriate for India as this crop plays a vital role in ensuring nation's food security and is a means of livelihood for millions of rural households. India has the largest area under rice (44.6 million ha) with a production of about 104 million tons. The post-independence era has witnessed spectacular progress in enhancing the production and productivity of rice, thanks to the miracle semi-dwarf, photo-insensitive, fertilizer-responsive, and non-lodging varieties and matching production and protection technologies that heralded a new era known as the Green Revolution.

During the Green Revolution era, the growth rate of rice (2.3%) was higher than population growth and thus there was surplus production [1]. But now, with the onset of second-generation problems, such as soil fatigue, declining water table, and, most important, climate change, production and productivity gains of rice are a big question mark. Rice production is intrinsically linked with land and water, and this has unique and profound implications for the environment. In the highly intensive rice-wheat cropping system of the north-west India, seasonal wet and dry crop cycles, increased fertilizer usage, a heavy reliance on irrigation water accompanied with indiscriminate burning of crop residues are the main features.

The emission of greenhouse gases (GHGs) in the rice-wheat system and other environments associated with food grain production now begs for attention [2]. Climate change as the consequence of global warming and depletion of the ozone layer is already being experienced across the world. Global warming is the phenomenon in which GHGs, such as CO_2, CH_4 and N_2O, act as a shield and trap solar heat and keep it from escaping into outer space, thereby increasing Earth's mean surface temperature [3].

Rice production contributes to global climate change through the emission of CH_4 and N_2O and in turn, suffers the consequences of climate change [4]. Rice is already grown under a prevailing threshold of high temperature and reduced water availability, making it increasingly vulnerable to such changes in the climate [5,6]. With the increase in rice production in the Indo-Gangetic Plains (IGP), there is an increase in the production of rice straw as well and about 80% of the straw is burned in the field, particularly after combine-harvesting rice, thus causing a huge nutrient loss. At the current price, the cost of N, P_2O_5, and K_2O lost in residue burning is about 4.7 billion Indian rupee in Punjab (1 US$ ≈ 50 Indian Rupees). Besides nutrient loss, burning of rice straw causes air pollution [7].

An increase in temperature due to global warming has two effects on rice: increase in respiration due to higher minimum temperature and decrease in spikelet fertility due to higher maximum temperature [8]. The increase in temperature, especially mean minimum night-time temperature, has adverse effects on rice productivity as it reduces crop duration, increases respiration rate, alters photosynthate partitioning to grains, affects the survival and distribution of pest populations, hastens nutrient mineralization in soils, decreases fertilizer-use efficiency, and increases evapo transpiration [9-11].

An increase in atmospheric CO_2, on the other hand, has a fertilization effect on rice, promoting its growth and productivity. Recent studies, however, suggest that the effect of global warming would have negative influence on rice production due to increased respiration that resulted into shortened vegetative and grain-filling period [12].

Nelson et al. [13] reported that during 2000, South Asia and world rice production was 120 and 391 million metric tonnes (mmt), respectively (Table 1). With no climate change, production is predicted to increase to 169 and 455 mmt for South Asia and World, respectively, in 2050; an increase of 41% and 17% for South Asia and world, respectively. With the CSIRO (Commonwealth Scientific and Industrial Research Organization, Australia) model, South Asia and world production of rice in 2050 will be 14 and 12% lower, respectively, than with no climate change in 2050. Similarly with the NCAR (National

***Corresponding author:** Bhagirath Singh Chauhan, Weed Scientist, International Rice Research Institute, Philippines, E-mail: b.chauhan@irri.org

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Details	South Asia	World
2000 (mmt)	120	391
2050 No CC (mmt)	169	455
2050 No CC (% change)*	41	17
CSIRO (% change)**	-14	-12
NCAR (% change)**	-15	-14

*2050 No CC=the % change between production in 2000 and 2050 with no climate change.
**CSIRO and NCAR=the additional % change in production in 2050 due to climate change relative to 2050 with no climate change.

Table 1: Climate change effect on rice production (million metric tonnes), no CO_2 fertilization [13].

Center for Atmospheric Research, US) scenario, South Asia and world production of rice in 2050 will be 15% and 14% lower, respectively, than with no climate change in 2050.

It is also believed that climate change would affect the quality of crops, particularly important aromatic crops, such as basmati rice. Results from climate change studies in the northwest India by a group of scientists in the Climate Research Unit, University of East Anglia, UK, reported that a rise in mean temperature of about 2°C in the Indian states of Punjab and Haryana would decrease rice yields in these states [14]. Increased atmospheric CO_2 content in the arid regions of India may results into enhanced productivity of C_3 plants; however, such gains attributed to CO_2 might be offset by increase in temperature.

Thus, it appears that in the northwest India, the anticipated climate change may have overall negative influence on agriculture. The positive effects of an increase in CO_2 concentration on growth and yield of rice are nullified by a simultaneous increase in temperature [15]. The CO_2 concentration has to rise to 450 mg kg^{-1} to nullify the effect of a 1°C increase in temperature and to 550 mg kg^{-1} to nullify the negative effect of a 2°C increase in temperature.

The estimated total annual output of CH_4 into the atmosphere from all sources in the world is 535 Tg $year^{-1}$. Although the increase in annual load of CH_4 in the atmosphere is lower than that of CO_2, its higher global warming potential as compared to CO_2 account for its major contribution (15-20%) to global warming. India's total contribution to global CH_4 emissions from all sources is 18.5 Tg $year^{-1}$. Agriculture, mainly rice and ruminant animals, is the major source of these emissions. International studies indicated that as much as 110 Tg $year^{-1}$ of CH_4 was released from rice paddies alone [16,17]. Sinha [18] estimated that annual global CH_4 emissions from rice paddies are less than 13 Tg $year^{-1}$ and the contribution of Indian paddies to this is estimated to be 4.2 Tg $year^{-1}$ or 32.3% of total. Scientists can thus play an important role in creating awareness about this and prepare agriculture for climate change through sound mitigation and adaptation strategies.

Mitigation and Adaptation Measures

To counter the anticipated impact of climate change, mitigation and adaptation strategies must be strengthened. While we face a major challenge of increasing rice production against the backdrop of reduced area, and scarcity of water and other inputs, climate change is likely to have a catastrophic effect on rice production unless we start tackling the problems immediately. Mitigation of the causal factors and adaptation of the crop to changing climate are two broad strategies to restrain and cope with changing climate: mitigation strategies aim at reducing the emission of GHGs into the atmosphere and adaptation involves enabling the plant to perform optimally under adverse climatic conditions through suitable cultural and genetic strategies.

Cultural Strategies

Efficient water use

Cycle, periodicity, and intensity of rainfall during the monsoon determine the fate of rice farmers and this cycle is changing due to climate. Weather data revealed that drought in some years was very serious and, therefore, the efficient use of irrigation is very important for sustainable rice production [19]. A significant decreasing trend of monsoon-season rainfall was noted in the eastern part of India, Kerala, Himachal Pradesh, and Uttarakhand from 1991-2003.

Rice consumes almost 50% of irrigation water used for all crops and the water crisis that we are facing today is a great threat to rice cultivation. The declining availability of water and increased competition from domestic and industrial sectors are affecting the sustainability of rice in the IGP. Many districts in the rice-growing areas of the northwestern IGP show a groundwater table decline of 3-10 m year-1 during the last two decades [20].

The groundwater table has been falling by about 54 cm year-1 in central Punjab [21]. The other side of the water problem is waterlogging in some areas, especially in the southwestern part of Punjab [22]. Therefore, the future of rice cultivation mostly depends on developing and adopting technologies that would ensure efficient water use. Water application in rice needs to be decreased by increasing water-use efficiency through reduced losses caused by seepage, percolation, and evaporation; laser land levelling; crack ploughing to reduce bypass flow; and bund maintenance [23].

Management options for high efficient use of rainwater include diversified cropping, crop scheduling, and the construction and maintenance of small ponds to be used as reservoirs for rainwater harvesting. Various crop- and water-management systems, such as water-saving techniques, alternate wetting and drying, growing rice-wheat with reduced or no-tillage either on flat or raised beds, and shifting away from continuously flooded (anaerobic) to partly or even completely aerobic rice can drastically improve the efficiency of water use [24]. It is time to initiate a movement like 'more crop per drop of water', which has been quite successful in Israel. Aerobic dry-seeded rice is one such option to minimize the water requirement of the rice crop.

Growing rice with aeration or under non-flooded conditions is referred to as 'aerobic rice'. Work on aerobic rice has begun at different research centres and this includes the development of suitable varieties and hybrids for aerobic conditions, optimizing the agronomic/cultural practices for successful aerobic cultivation, examining nutritional and quality aspects, and studying the changing scenario of pests and diseases. With the development of aerobic rice technology, it would be possible to obtain a reasonably good yield, with 20-30% savings of irrigation water. With aerobic rice production, CH_4 emissions from rice fields could be mitigated [25].

Flooded rice culture with puddling and transplanting is considered one of the major sources of CH_4 emissions and accounts for 10-20% of total global annual CH_4 emissions [26]. Due to individual or combined effects of various factors, such as climatic conditions, soil pH, redox potential, soil texture, soil salinity, temperature, rainfall, and water management, amount of CH_4 emission varies between different crop establishment techniques [27,28]. CH_4 emission starts at redox potential of soil below -150 mV and is stimulated at less than -200 mV [29].

CH_4 emission and global warming potential were highest under conventional transplanted rice and emission of N_2O was highest under direct-seeded rice crop with conservation practice of brown manuring because the addition of organic matter to soil increased the decomposition rate, which resulted in higher emission of GHGs [30]. These results suggest the need to deploy strategies to reduce N_2O emissions from direct-seeded rice for minimizing adverse impacts on the environment. This tradeoff between CH_4 and N_2O emission is a major hurdle in reducing global warming risks and therefore, strategies must be devised to reduce emissions of both CH_4 and N_2O simultaneously. There is a need to developing water management practices in such a way that soil redox potential can be kept at an intermediate range (-100 to +200 mV) to minimize emissions of both CH_4 and N_2O [31].

Although aerobic rice may reduce CH_4 emissions from rice fields, it may results into increased N_2O emissions. The N_2O is having 310 times global warming potential than CO_2. The trick is to find a way to maximize the benefit of positive aspects and minimize the environmentally negative effects [32]. These authors also suggested that N_2O emissions can be mitigated using an appropriate combination of irrigation timing and N application. In the fallow period, crop residue must be incorporated in the soil, so that it can decompose faster as compared to when it was scattered on the soil surface. This may results in high CO_2 emission during fallow period and lower CH_4 emission during the period of follow crop. Thus, the global-warming impact of rice farming can be reduced with early incorporation of crop residue [32].

Integrated practices

To reduce the emissions of GHGs in rice production, integrated practices are needed. This would be possible through integrated crop management strategies involving best management practices, such as altering planting time and integrated nutrient and pest management systems. The introduction of "soil health card system" containing information on soil quality parameters for farmers to monitor the health of their soil and ensure that soil fertility is enriched and not depleted would be an important step toward preserving soil quality and reducing emissions of GHGs. The use of resource-conserving technologies, including zero- or minimum-tillage with residue mulch, integrated nutrient management, and crop diversification, is an alternative to conventional practices used in rice-wheat systems for improving soil quality and conserving the environment [33].

In the rice-wheat cropping system, nitrogen-use efficiency (NUE) is only 30-35%, which causes environmental and ecosystem deterioration. Large amounts of nutrients percolate into the groundwater. Eutrophication of water bodies due to high nitrate concentration and the increasing level of nitrates in drinking-water sources are a serious concern [34]. Significant improvement in NUE is therefore crucial, and NUE can be improved by adopting integrated fertilizer, soil, water, and crop management techniques that could results into minimize N losses, optimize indigenous soil N supply and maximize crop N uptake.

The key to improving NUE is the synchrony between N supply and demand. The leaf color chart in rice, a promising, inexpensive, and eco-friendly technology, can help farmers in monitoring plant N status, irrespective of the type of N (organic, biologically fixed, or chemical) applied, and to apply N fertilizer only when the crop needs it [35]. Climate change also leads to shifts in the incidence, migration, and viability threshold of pests. Today, rice production and farmers' lives are already affected by the pest management practices they adopt. Hence, understanding the intricacies of climate change vis-à-vis rice pests is crucial. Climate change would shift pest incidence, namely, temperature, precipitation distribution, and wind pattern therefore may results in shift in pest populations. Therefore, a continuous watch is needed on climate change and its consequences. The non-judicious use of pesticides has caused a large problem of air, water, and soil pollution in rice-wheat growing regions.

A part of the applied pesticides, irrespective of crop, applicator, or formulation, ultimately escapes to the soil, water, and food chain, causing human health problems, such as cancer, reduced life span and fertility, increased cholesterol levels, high infant mortality, and varied metabolic and genetic disorders. Efforts should be made to reduce pesticide use and adopt integrated pest management (IPM) strategies to reduce pesticide pollution. The use of biotechnological approaches, such as bioremediation using fungi, bacteria, and other microbes, may help in alleviating this problem in areas where pollution has already reached a serious level. Phytoremediation involving the use of high-latitude terrestrial plants could be another option for the remediation of polluted soils [36].

Burning of rice straw emits CO_2, CO, N_2O, SO, and suspended matter in the air. One potential solution to the problem of rice straw burning is its retention on the soil surface. This straw mulch reduces moisture loss from the soil, controls weeds, manipulates soil temperature for better crop growth, and improves soil organic matter content. With the development of new machines, such as the Happy Seeder/Turbo Seeder, it is now possible to sow seeds in a residue-retained field [37].

Genetic Strategies

Genetic strategies for coping with the adverse effects of climate change can be designed, taking advantage of the natural variation available in the germplasm and alien genes accessible from different biological sources. For instance, gene resources that can benefit from rising CO_2 concentration have been reportedly found in rice varieties, such as IR8, Dular, etc. Crop improvement with the aim of tailoring new rice cultivars that can maintain spikelet development in the scenario of high temperature and with comparatively less wasteful maintenance respiration losses is thus likely to provide twin benefits of sustained food production as well as reduced GHG emissions from rice fields.

Other potential impacts may include (i) increased net removal of atmospheric CO_2, (ii) increased and more stable yield potential and better response to current atmospheric CO_2 levels, due to increased net assimilation, (iii) reduced CH_4 emissions due to increased sink size and reduced belowground carbon release for methanogenesis, and (iv) reduced fossil fuel use due to increased NUE. To achieve this, research must be focussed to identify the physiological and genetic controls processes involved in rice adaptation to heat.

Now, an urgent need is to breed short-duration varieties having high water productivity and per day productivity and varieties that can adapt to a wide range of temperatures. PAU-201, a new cultivar of rice developed by the Punjab Agricultural University, India, is an excellent example of such a variety that maintains its yield even under late-sown conditions [38]. Similarly, many heat- and high temperature-tolerant varieties are known to exist. Cultivars that can flower early in the day (e.g. between 0600 and 0800 hour) and thus escape high-temperature stress have been identified [39].

Exploiting the existing genotypic variation in flowering time (especially, the wild-type) serves as a useful mitigation option for rising temperature. Introgression of the early morning flowering gene from *Oryza officinalis* into *O. sativa* has recently been shown to have positive effect on reducing the spikelet fertility [40]. Using such sources, the desired genes can be recombined in varieties of choice by conventional as well as molecular breeding approaches.

Desirable traits from modern lowland varieties, such as high yielding, resistance to multiple pests and diseases, etc., and the drought resistance from upland varieties could be combined in breeding programs [41]. Large scale screening of rice germplasm, including the wild relatives, should be the starting point to investigate if the dilemma between high yielding and drought resistance could be broken. Wild rice accessions with drought resistance as well as faster growing speed will be valuable in the breeding of cultivated rice varieties which can produce high biomass and grain yield under irrigated and rainfed conditions. A recent study reported that *O. rufipogon* accessions from tropical areas have stronger drought resistance than accessions from sub-tropical areas [42].

Frequent floods have also been common in recent years, suggesting imminent climate change. The development of submergence-tolerant varieties, such as Swarna-Sub1 and IR64-Sub1, exemplifies the technological feasibility to overcome some of the problems related to climate change [43]. The commendable work on sequencing the rice genome has great significance in understanding the function of genes and their manipulation for rice improvement. Research efforts are under way to make C3 rice perform like C4 plants through efficient assimilation of carbon via recombinant DNA technology and use of prospective genes, such as phosphoenol pyruvate carboxylase (*PEPC*) [44,45]. Therefore, it is essential to tailor new varieties that can adapt to the adverse effects of climate change and still have high yield.

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