

Assessment of climate change impact on rice using controlled environment chamber in Tamil Nadu, India

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Impacts of elevated temperature and carbon dioxide (CO₂) enrichment on rice were assessed by carrying out an experiment with four dates of planting (1 June and 15 June, 1 and 15 July) during 2014 under two different environmental conditions, viz. ambient and modified (climate control chamber) with +4°C compared to the ambient temperature and CO₂ enrichment of 650 ppm. Crops grown under modified environment recorded reduced growth characters (leaf area index, dry matter production, number of tillers m⁻²), lesser dry matter partitioning towards grain, yield attributes (number of productive tillers m⁻², number of filled grains panicle⁻¹) and lower grain yields compared to those grown under ambient condition. Crops subjected to elevated temperature and enriched CO₂ attained panicle initiation, flowering and maturity earlier than those under open ambient condition.

Keywords: Ambient and modified environment, climate change impact, elevated temperature, enriched carbon dioxide, rice.

RISING fossil-fuel burning and land-use changes have emitted and are continuing to emit greenhouse gases (GHGs) into the earth's atmosphere. A rise in these gases has caused a rise in the amount of heat from the sun withheld in the earth's atmosphere that would normally be radiated back into space. This increase in heat has led to the greenhouse effect, resulting in climate change. Warming of the climate system is unequivocal, as is now evidenced by the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report¹. The 0.74°C increase in temperature trend for 100 years (1906–2005) is mainly attributed to human-induced GHG emissions in the past¹ and is expected to contribute more in the future. Climate change will have wide-ranging effects on the environment, and on socio-economic and related sectors, including water resources, agriculture and food security, human health, terrestrial ecosystems and biodiversity and coastal zones. Rice is the staple food for most people living in Asia; it provides 23% of the global human per

capita energy and 16% of the per capita protein². India ranks first in area under rice (about 45 m ha) and second in production next to China. Occurrences of climatic extremes especially at critical growth stages of rice significantly reduce the yield³. According to Alam *et al.*⁴, one of the significant options for the agricultural sector in tropical Asia is 'to adjust cropping calendar to deal with climatic variability/change and extremes'. Evaluating the effect of different sowing dates could be one of the most important operational strategies to avoid harmful effects on critical stages under elevated temperatures and carbon dioxide (CO₂) levels. In the present study, four dates of sowing were chosen for understanding the effect of sowing time under current and future climatic conditions. As rice is more responsive to climatic factors, any changes in climate will have an impact on the productivity of rice. Enriched CO₂ under different elevated temperature levels would also affect the rice crop. Temperature increases in different (tropical, subtropical and temperate) climate regions may create a positive or negative effect on rice crops, depending upon the location. For instance, in the Mediterranean region, temperature increase would enhance establishment of rice crop, where cool weather severely affects crop establishment⁵. In contrast, a similar temperature increase would diminish the favourable effects of low night temperature (16–21°C) on grain production in northern Japan⁶. Mohandass *et al.*⁷ reported a yield decrease of 14.5% for summer rice crops across nine experiment stations in India based on the Hadley-coupled model projection. Though earlier studies have reported the combined effects of elevated CO₂ and temperature on rice^{8,9}, the CO₂ and temperature levels considered in them were different from the changes in climate projected over the Indian sub-continent; besides, the effects were studied with one sowing window. IPCC predicted (with medium to low confidence) in its Fourth Assessment Report that in mid- to high-latitude regions, moderate warming of the atmosphere (1–3°C) can benefit crop yields by increase in CO₂ concentration and rainfall changes, while similar increases (1–2°C) have a negative effect on major crop production in low-latitude regions¹⁰. Tripathy *et al.*¹¹ reported that wheat and rice show an

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increase in yield with 2°C rise in temperature at doubled CO₂ concentration in India. The increase in temperature will not offset CO₂ concentration at all levels, and the magnitude of elevated temperature effects would vary with different CO₂ concentration levels. The present study quantifies the likely impact of projected climate (4°C increase in temperature with CO₂ concentration of 650 ppm) on rice crop.

Materials and methods

A study conducted using PRECIS (providing regional climate for impact studies) regional climate model indicated warming trend in all agro-climatic zones of Tamil Nadu, India, up to 4.6°C at the end of the century (2100) compared to the baseline mean annual temperature (1961–1990)¹². The CO₂ levels are expected to increase continuously and by the end of the century, majority of the predictions report doubling of CO₂ in most parts of the world, including India^{13–16}. In the present study, based on the above research outcomes, it has been decided to maintain the CO₂ levels inside a climate control chamber (CCC) at 650 ppm and increase the temperature by 4°C compared to the outside temperature.

Weather management in climate control chamber

The CCC has been set-up at Agro Climate Research Centre, Tamil Nadu Agricultural University (TNAU), Coimbatore. It has a total area of 25 m² (5 m × 5 m) with a column height of 4 m and fabricated using galvanized steel pipes. The roofing and outer walls have been constructed with polycarbonate material. Two sets of weather sensors for recording air temperature at any required interval are placed inside as well as outside the chamber. Inside the chamber, the required levels of temperature and CO₂ are maintained by giving commands through the control panel. The temperature control is made in such a way that the sensors outside the chamber would sense the ambient temperature and the control panel would adjust the temperature inside the chamber by operating a fan, fogger and lid valve set up in the chamber. It is possible to raise the temperature inside the chamber by +0.5°C, +1.0°C, +1.5°C, ..., +7°C compared to the outside ambient temperature. This set-up has been made keeping in mind that the expected temperature increase by the end of the century would be from 3°C to 6°C over the Indian subcontinent¹⁷. CO₂ enrichment is made through the control panel by pumping in and regulating its flow from the cylinders inside the chamber so as to constantly maintain the required level of CO₂. Based on the experimental set-up, CO₂ levels ranging from 370 to 900 ppm could be maintained throughout the day. The data logger stores the data/history of the environment conditions maintained inside and outside the chamber and could be easily downloaded for any assessment.

Impact assessment of elevated temperature and CO₂ on rice

For assessing the impact of elevated temperature and CO₂ on rice growth, phenology and productivity, experiments were conducted in open ambient condition as well as under CCC.

Experimental details

Preparation of experimental tanks and transplanting:

The experiment was carried out in large tanks made up of reinforced fibre plastic – 85 cm breadth × 142 cm length × 50 cm depth. Soil was transported from the wetland paddy field of TNAU and filled inside the tank to a depth of 40 cm. Soil in the experimental tanks was thoroughly prepared like a puddled soil and levelled properly. Then 15-day-old seedlings of rice hybrid CORH2 were transplanted inside the tanks by maintaining a spacing of 20 × 10 cm. Rice was planted at four dates, viz. D₁, 1 June; D₂, 15 June; D₃, 1 July and D₄, 15 July during 2014, under two different environmental conditions, viz. ambient and modified environmental condition with +4°C than the ambient temperature and CO₂ enrichment to 650 ppm with five replications in completely randomized design.

Biometric observations

In each tank five hills were selected at random and tagged for recording growth attributes such as plant height, leaf area index (LAI), tiller production, dry matter production at maximum tillering, flowering and harvesting stages, dry matter partitioning and yield attributes such as number of productive tillers m⁻², number of filled grains per panicle as well as grain and straw yield. Phenology of rice crop days to panicle initiation, 50% of flowering and physiological maturity were also recorded.

Leaf area index: LAI of rice was worked out using the formula as suggested by Palanisamy and Gomez¹⁸

$$\text{LAI} = \frac{L \times W \times N \times K}{\text{Plant spacing (cm)}}$$

where L is the length of the third leaf from the top in a tiller (cm), W , the maximum width of the same leaf (cm), N the number of leaves per hill and K is a constant factor (0.75).

Dry matter production and partitioning: Plants were removed from sample rows, the samples were dried in shade and then in a hot-air oven at 80°C for 72 h to reach a constant weight. Then, dry weight was recorded.

Productive tillers: Ear-bearing tillers alone were counted in five tagged plants in each tank and the mean value was expressed as productive tillers m^{-2} .

Statistical analysis: The data on various characters studied were statistically analysed as suggested by Gomez and Gomez¹⁹. Wherever the treatment difference was found significant by the *F* test, the critical differences were constructed at 5% probability level and the values furnished. The treatment differences that were non-significant at 5% were denoted as 'NS'.

Results

Phenology of rice under ambient and modified climatic conditions

Crops grown under CCC (E_2) with increased temperature and CO_2 enrichment attained panicle initiation, flowering and maturity earlier than those grown under open ambient condition (E_1). Crops planted on 15 July (D_3) came to physiological maturity six days earlier than those planted on 1 June. Crops grown under CCC (E_2) came to physiological maturity seven days earlier than those grown under open ambient condition (E_1 ; Figure 1).

Rice growth under open ambient and modified climatic conditions

Plant height: In general, plant height gradually increased with age of the crop and maximum plant height was recorded during the harvesting stage. Plant height was more under CCC compared to open ambient conditions (Figure 2 a). During maximum tillering stage, the plant height (cm) was significantly influenced by planting

time (D) as well as environmental conditions (E). Crops planted on 1 June (D_1) grew taller (66.23 cm) followed by those planted on 15 June (D_2), which recorded 63.12 cm height. The crops planted on 1 July (D_3) and 15 July (D_4) recorded plant height of 59.27 and 56.40 cm respectively. The treatment E_2 (CCC) produced significantly taller plants (65.1 cm) than those grown under open ambient conditions (E_1). The plant height followed similar trend in the flowering stage as that of the maximum tillering stage. The treatment D_1 showed significantly more plant height (81.29 cm) followed by D_2 (74.79 cm), D_3 (71.14 cm) and D_4 (66.84 cm). Enhanced temperature and CO_2 levels positively influenced the plant height at flowering and produced significantly taller plants. Similar trends were followed in the harvesting stage also.

Leaf area index: LAI increased with age of the crop and maximum LAI was recorded during harvesting stage. During maximum tillering, flowering and harvesting stages, D_1 (1 June planted) recorded significantly higher LAI of 0.68, 1.24 and 1.04 respectively than D_4 (15 July planted), which recorded the least LAI values among all the dates of planting. At all the growth stages, minimum LAI was observed with D_4 (15 July planted) treatment. Between the two different environmental conditions used, maximum LAI was registered in the open ambient condition (E_1) compared to elevated levels of temperature and CO_2 maintained under CCC (E_2) at all the growth stages (Figure 2 b).

Number of tillers per square metre: As shown in Figure 2 c, at maximum tillering stage, crops planted on 1 June (D_1) produced significantly higher number of tillers (1376) followed by D_2 (1238) and D_3 (1126) crops. The lowest number of tillers/sq. m was produced with the treatment D_4 (985). Significantly higher number of tillers (1288) was produced under E_1 , while E_2 recorded 1075 tillers m^{-2} . Maximum number of tillers m^{-2} was produced when the crop was planted on 1 June under open ambient condition (1450 tillers m^{-2}). In contrast, minimum number of tillers (820 m^{-2}) was produced under CCC with 4°C elevated temperature and 650 ppm CO_2 level in 15 July planted crop.

Dry matter production: The total dry matter production (DMP) (Figure 2 d) at harvest showed gradual decrease with delay in planting time. 1 June planted crops (D_1) recorded significantly higher DMP of 15,129 $kg ha^{-1}$ (+11.0% and 17.9% over D_2 and D_3) while it was 13,623 and 12,830 $kg ha^{-1}$ for 15 June (D_2) and 1 July (D_3) planted crops respectively. The crops planted on 15 July (D_4) recorded the lowest DMP of 11,162 $kg ha^{-1}$. DMP was negatively impacted under controlled environment (E_2) with elevated temperature and CO_2 enrichment (11,775 $kg ha^{-1}$). Plants grown under ambient environment (E_1) produced 14,597 $kg ha^{-1}$ of total dry matter.

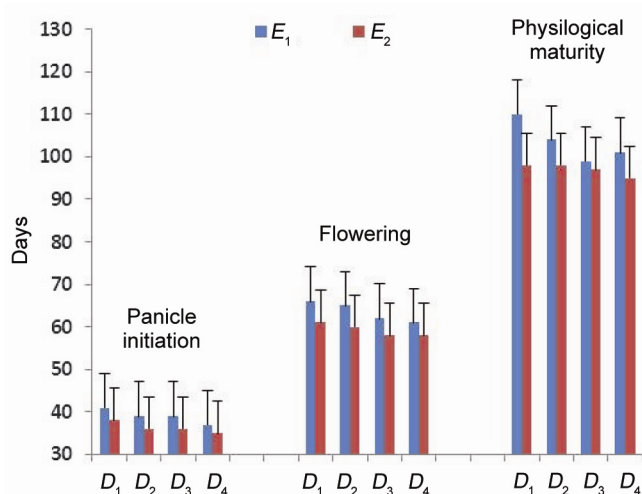


Figure 1. Phenology of rice under open ambient versus modified climate (+4°C temperature and 650 ppm CO_2) for different dates of planting. Open ambient condition (E_1), climate control chamber (E_2). D_1 , 1 June; D_2 , 15 June; D_3 , 1 July and D_4 , 15 July planted.

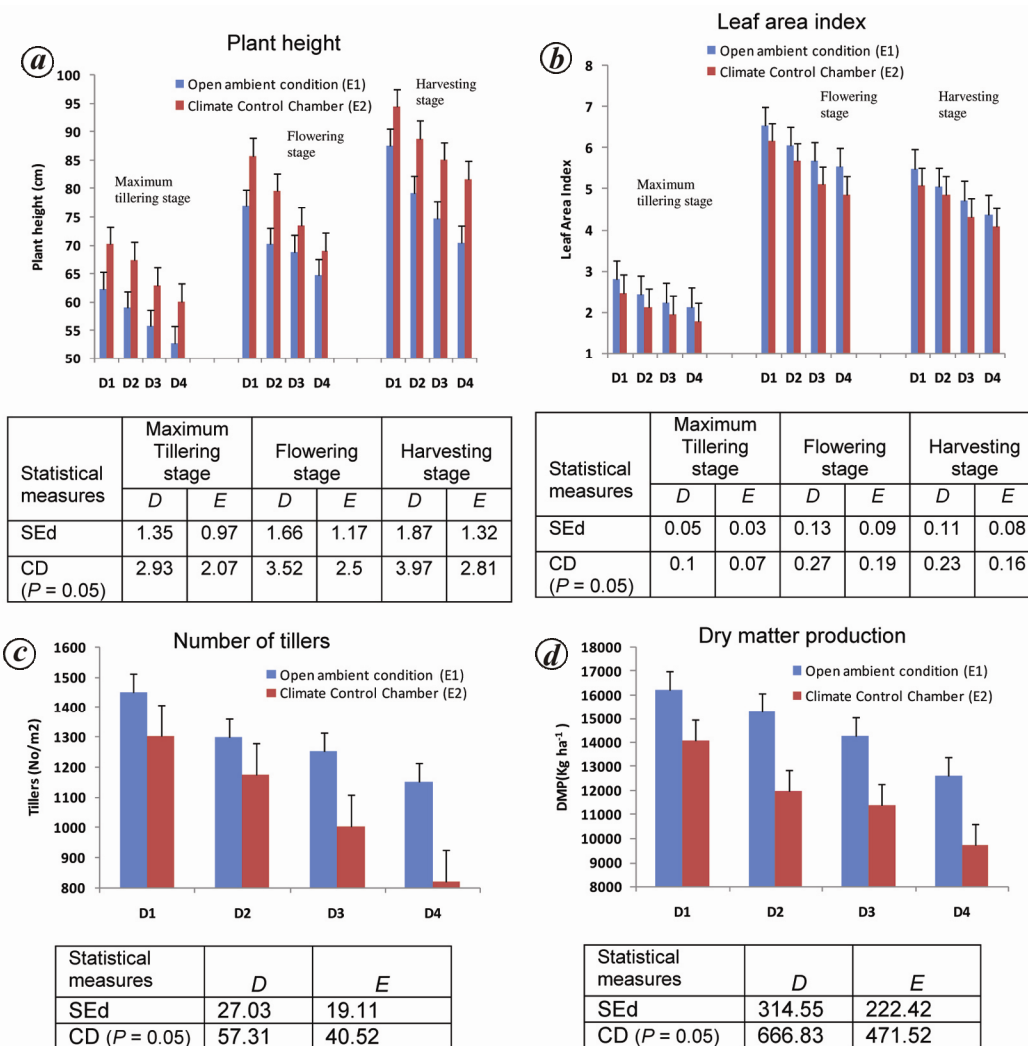


Figure 2. Effect of open ambient and modified climate (+4°C temperature and 650 ppm CO₂) on rice growth during different dates of planting.

Maximum dry matter (+66.7% higher over D_4 under CCC) was accumulated when the crops were planted on 1 June under open ambient condition (16,204 kg ha⁻¹) and lowest DMP was observed under CCC in 15 July planted crop (9719 kg ha⁻¹).

Dry matter partitioning: Crops grown under open ambient (E_1) and CCC (E_2) partitioned 26.3% and 20.2% of total dry matter respectively, to leaf and 28.5% and 30.9% respectively, to stem. From the total dry matter, 35.1% and 33.6% were partitioned to grain under open ambient and controlled condition respectively (Table 1).

Yield parameters, yield of rice under ambient and modified climatic condition

Yield-attributing parameters such as number of productive tillers m⁻², number of filled grains/panicle as well as

grain and straw yield as influenced by different dates of planting and environmental condition are presented in this section.

Productive tillers per square metre: In general, the number of productive tillers m⁻² (Figure 3a) was more under open ambient conditions than in controlled environment. The crops planted on 1 June (D_1) produced significantly higher number of productive tillers m⁻² (977) followed by those planted at 15 June (D_2 : 842) and 1 July (D_3 : 777). Least number of productive tillers m⁻² was recorded under 15 July (D_4 : 660) planted crops. The crops planted under open ambient condition (E_1) produced significantly higher number of productive tillers m⁻² (887), and E_2 recorded the lowest number of productive tillers m⁻² (741). The 1 June planted crops under open ambient condition recorded the highest number of productive tillers m⁻² (1030). Minimum productive

Table 1. Dry matter partitioning (DMP; kg ha⁻¹) at harvesting under open ambient versus modified climate (+4°C temperature and 650 ppm CO₂) for different dates of planting

| Treatment | Leaf | Stem | Root | Grain | Total DMP |
|---|-------------|-------------|-------------|-------------|-----------|
| Dates of planting (<i>D</i>) | | | | | |
| <i>D</i> ₁ : 1 June | 3838 (25.4) | 4331 (28.6) | 1507 (10.0) | 5453 (36.0) | 15129 |
| <i>D</i> ₂ : 15 June | 3581 (26.3) | 3784 (27.8) | 1510 (11.1) | 4748 (34.9) | 13623 |
| <i>D</i> ₃ : 1 July | 3417 (26.6) | 3637 (28.3) | 1485 (11.6) | 4291 (33.4) | 12830 |
| <i>D</i> ₄ : 15 July | 2796 (25.0) | 3245 (29.1) | 1451 (13.0) | 3670 (32.9) | 11162 |
| SEd | 144.43 | 111.41 | 40.18 | 411.8 | 301.02 |
| CD | 306.2 | 236.2 | NS | 873.1 | 638.15 |
| Environment (<i>E</i>) | | | | | |
| <i>E</i> ₁ : open ambient condition | 3844 (26.3) | 4158 (28.5) | 1468 (10.1) | 5127 (35.1) | 14597 |
| <i>E</i> ₂ : climate control chamber | 2374 (20.2) | 3639 (30.9) | 1809 (15.4) | 3953 (33.6) | 11775 |
| SEd | 93.36 | 74.34 | 31.98 | 265.94 | 212.85 |
| CD | 197.0 | 157.6 | 67.8 | 563.8 | 451.24 |

SEd, Standard error; CD, Critical difference.

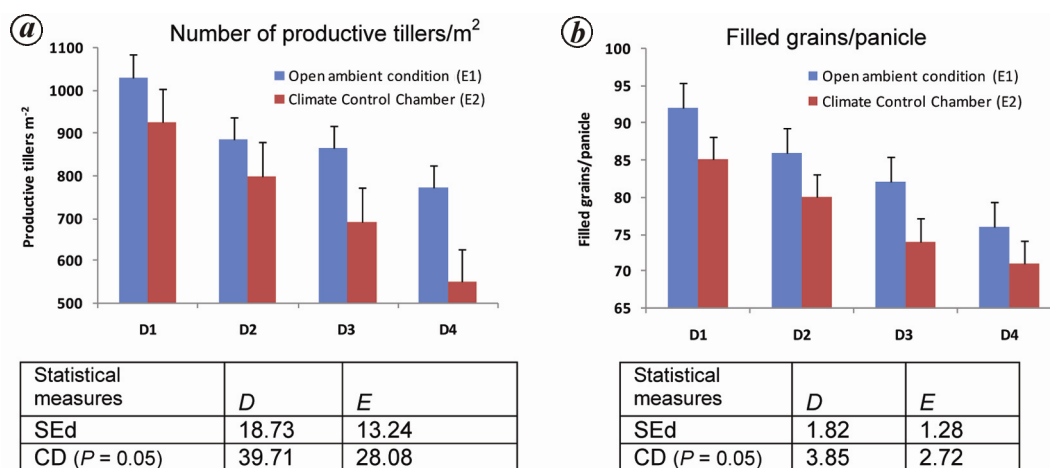


Figure 3. Yield parameters under open ambient versus modified climate (+4°C temperature and 650 ppm CO₂) for different dates of planting.

tillers m⁻² was registered under CCC in 15 July planted crops (549).

Number of filled grains per panicle: Significantly higher number of filled grains was produced in crops planted on 1 June (*D*₁: 89) followed by 15 June (*D*₂: 83; Figure 3 b). The treatments *D*₃ and *D*₄ registered the lowest number of filled grains/panicle and both treatments were at par with each other. The crops planted under open ambient conditions (*E*₁) recorded significantly higher number of filled grains per panicle (84) compared to those grown under CCC (*E*₂; 78).

Grain yield: Comparing different dates of planting treatment, the crops planted on 1 June (*D*₁) recorded significantly higher grain yield (5453 kg ha⁻¹) followed by 15 June planted crops (*D*₂: 4748 kg ha⁻¹) and 1 July planted crops (*D*₃: 4291 kg ha⁻¹). Poorest performance was exhibited by the 15 July (*D*₄) planted crops that recorded the lowest grain yield of 3670 kg ha⁻¹. The crops grown under open ambient conditions (*E*₁) recorded significantly higher grain yields (5127 kg ha⁻¹) compared

to those grown under CCC (*E*₂; grain yield of 3953 kg ha⁻¹). The crops planted on 1 July (*D*₁) produced more grain yield (6144 kg ha⁻¹) under open ambient condition (*E*₁). The crops planted on 15 July under CCC (*E*₂) environment produced the lowest (48.7% lower than *D*₁ planting under *E*₁) grain yield of 3151 kg ha⁻¹ (Figure 4).

Straw yield: The straw yield was highest under 1 June planted crop (*D*₁) (8169 kg ha⁻¹) (Figure 4). However, *D*₁ was at par with 15 June planted crop (*D*₂) that recorded 7365 kg ha⁻¹ straw yield and was significantly superior over the rest of the planting dates (*D*₃ and *D*₄). The 1 July planted crops (*D*₃) registered 7054 kg ha⁻¹ straw yield which was at par with *D*₂. Minimum straw yield of 6041 kg ha⁻¹ was produced by the 15 July sown crops (*D*₄), that was significantly lower than all the other planting dates. The crops planted under CCC (*E*₂) recorded less straw yield (7998 kg ha⁻¹) compared to those grown in open ambient condition (*E*₁: 6316 kg ha⁻¹). Higher straw yield was produced with 1 July planting under open environment (8563 kg ha⁻¹).

Discussion

Effect of ambient and modified climatic conditions on phenology of rice crop

From the experimental results, it can be observed that the days to physiological maturity decreased with delay in planting from 1 June (D_1) to 15 July (D_4) (Figure 1). This might be due to variation in temperature during different crop-growing phases. The observed weather conditions that prevailed during crop growing period with 1 June and 15 July planting clearly showed that temperature variation occurred between June and July planting. The 1 June planting experienced less temperature (on average -2.5°C) during reproductive period compared to 15 July planting, which lengthened the days to physiological maturity. The crops grown in CCC (E_2) attained panicle initiation, flowering and maturity earlier than those grown under open ambient condition (E_1). The reduction in crop duration in CCC might be due to the fact that high temperature triggers higher activity of enzymes involved in the growth and development process.

Effect of ambient and modified climatic conditions on growth of rice crop

Plant height, leaf area index, tiller production and dry matter accumulation (Figure 2 *a-d*) decreased with delay in planting after 1 June (D_1) under both environmental conditions (E_1 and E_2). 1 June planted crops might have experienced better environmental conditions that may have resulted in good growth and produced taller plants, more leaf area, maximum number of tillers and dry matter accumulation compared to other dates of

Planting²⁰. Mandal *et al.*²⁰ also found a negative relationship between LAI and advancement in sowing window. Increased plant height was noticed under CCC with enhanced temperature and CO_2 levels compared to open ambient conditions. Increase in temperature and enhancement in CO_2 must have favoured cell elongation that might have resulted in taller plants in CCC. The outside average temperature was 31°C , whereas it was 35°C inside the chamber, which is relatively higher than the optimum temperature required for rice at different growth stages. Thus, the physiological activity of the plants grown inside the chamber may have been significantly affected with increased temperature. During the cropping period, the temperature even reached up to 39°C in the chamber, which could have marked effects on the growth and development of rice crop. Lower leaf area, reduced tillers and lesser DMP were recorded under CCC (E_2) compared to open ambient condition. This might be due to the impact of high maximum and minimum temperatures which prevailed inside the chamber that might have affected the carbon fixation and utilization rates. Even with enhanced CO_2 levels inside the chamber, 4°C increases in temperature must have reduced the rate of photosynthesis and increased the respiration rate, especially during the night hours. As a cumulative effect, the total dry matter production must have decreased under the modified climatic conditions compared to open ambient environment. Kim and Young²¹ found that overall, total grain dry matter (DM) increased with elevated CO_2 by 69.6% in ambient temperature, but decreased with elevated temperature by 33.8% in ambient CO_2 due to warming-induced floral sterility. Dry matter partition from shoot (source) to grain (sink) was reduced in the chamber compared to open ambient conditions. Rice plants grown under elevated temperature may have produced more number of infertile flowers, and the resultant decrease in sink size might lessen the dry matter allocation rate towards sink⁹.

Effect of ambient and modified climatic conditions on yield of rice crop

Rice crops planted on 1 June (D_1) yielded more compared to other dates of planting. When the planting dates were delayed, grain yield of rice declined gradually. Higher grain productivity in 1 June sown crops might be due to more number of productive tillers (Figure 3 *a*), and the higher number of filled grains (Figure 3 *b*) recorded under this treatment might be due to the prevalence of favourable weather conditions during different pheno phases of crop growth. Rice crops grown under open ambient condition (E_1) registered higher grain and straw yields (Figure 4) compared to plants grown under controlled condition (E_2). Lower yield in the chamber indicated that high temperature nullifies the CO_2 fertilization effect in

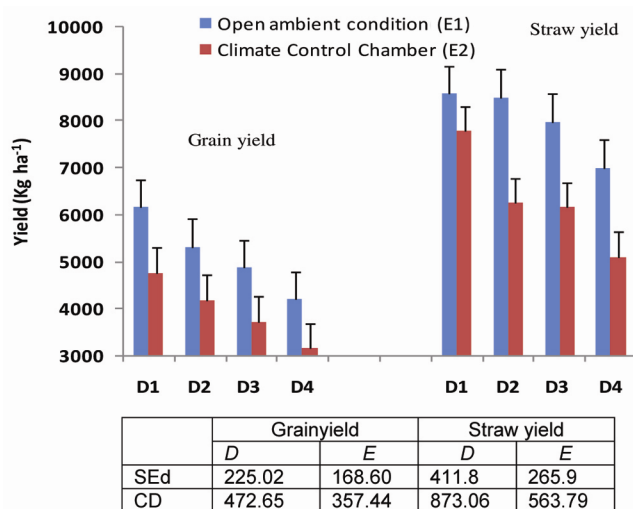


Figure 4. Influence of open ambient and modified climate (ambient + 4°C and CO_2 enrichment of 650 ppm) on grain and straw yield (kg ha^{-1}) for different dates of planting.

increasing yields. The negative effect of rising temperature on yield may be due to the fact that it increased the rate of respiration and shortened the vegetative and grain filling stages. Reduction in grain yield under CCC as witnessed in the present study might also be due to high temperature-induced sterility of rice spikelet. Horie²² reported that doubling of CO₂ concentration alone markedly enhanced crop dry matter production; however, increase in CO₂ concentration coupled with increase in temperature resulted in reduction of panicle dry weight and grain yield. The reduction in straw yield under modified environmental condition might be due to reduction in the number of tillers and dry matter production.

Conclusion

Crops grown under elevated temperature and in CO₂ enriched chamber showed panicle initiation, flowering and maturity earlier than those grown under open ambient condition. Days to panicle initiation, days to flowering and days to maturity decreased with delay in planting from 1 June. Crops grown under CCC (E₂) with elevated temperature (ambient +4°C) and CO₂ enrichment (650 ppm) recorded reduced growth characters such as number of tillers, LAI and dry matter production. Crops planted on 1 June registered higher growth characters like stem height, number of tillers, LAI and dry matter production than other dates of sowing. Studies indicated that significantly more dry matter was partitioned to the root when the plants were kept under warmer environment than under open ambient condition. The crops grown under controlled environment (E₂) partitioned lesser percentage of dry matter towards the grain compared to the plants grown under open ambient condition (E₁). Lower grain and straw yields were also recorded due to lesser number of productive tillers and lesser number of filled grains. Elevated temperature would nullify the enhanced CO₂ positive effect on rice growth and yield, and negatively impact the crop productivity.

1. IPCC, Summary for Policymakers, In Climate Change: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds Solomon, S. *et al.*), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.
2. International Rice Research Institute (IRRI). Rice Almanac, Manila, Philippines: International Rice Research Institute, 1997, 2nd edn.
3. Peng, S., Ingram, K. T., Neue, H. U. and Ziska, L. H. (eds), Climate Change and Rice. Los Banos, Philippines, 1996, pp. 3–8.
4. Alam, M. *et al.*, Impacts, Vulnerability and Adaptation to Climate Change in Asia: Background Paper for Meeting on Adaptation, Beijing, China, United Nations Framework Convention on Climate Change (UNFCCC), 11–13 April 2007.
5. Ferrero, A. and Nguyen, V. N., The sustainable development of rice-based production systems in Europe. *IRC Newsl.*, 2004, **54**, 115–124.

6. Matsushima, S. and Tsunoda, K., Analysis of developmental factors determining yield and application of yield prediction and culture improvement of lowland rice XLV. Effects of temperature and its daily range in different growth stages upon the growth, grain yield, and constitutional factors in rice plants. *Proc. Crop Sci. Soc. Jpn.*, 1958, **26**, 243–244.
7. Mohandass, S., Kareem, A. A., Ranganathan, T. B. and Jeyaraman, S., Rice production in India under the current and future climate. In *Modeling the Impact of Climate Change on Rice Production in Asia* (eds Mathews, R. B. *et al.*), United Kingdom, CAB International, 1995, pp. 165–181.
8. Ainsworth, E. A., Rice production in a changing climate: a meta-analysis of responses to elevated carbon dioxide and elevated ozone concentration. *Global Change Biol.*, 2008, **14**, 1642–1650.
9. Kim, H. Y., Lim, S. S., Kwak, J. H., Lee, D. S., Lee, S. M., Ro, H. M. and Choi, W. J., Dry matter and nitrogen accumulation and partitioning in rice (*Oryza sativa* L.) exposed to experimental warming with elevated CO₂. *Plant Soil*, 2011, **342**(1–2), 59–71.
10. Core writing team, Pachauri, R. K. and Reisinger, A., Contribution of working groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change IPCC, Switzerland, 2007, p. 104.
11. Tripathy, Rojalin, K., Chaudhari, N. and Patel, N. K., Evaluation of different methods to estimate incoming solar radiation. *J. Agrometeorol.*, 2008, **10** (Special Issue, Part 1), p. 174.
12. Geethalakshmi, V., Kokilavani, S., Nagarajan, R., Babu, C. and Poornima, S., Impacts of climate change on rice and ascertaining adaptation opportunities for Tamil Nadu state. In The Proceedings of the International Symposium on Agro Meteorology and Food Security Conducted by CRIDA, Hyderabad, 2008, pp. 21–22.
13. Houghton, J. T., MeiraFilho, L. G., Callander, B. A., Harris, N., Kattenberg, A. and Maskell, K. (eds). Climate Change. Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, 1995.
14. Keeling, C. D., Whorf, T. P., Wehlen, M. and Van der Pliht, J., Inter annual extremes in the rate of rise in atmospheric carbon dioxide since. *Nature*, 1995, **375**, 666–670.
15. Morison, J. I. L. and Lawlor, D. W., Interactions between increasing CO₂ concentration and temperature on plant growth. *Plant Cell Environ.*, 1999, **22**, 659–682.
16. Prinn, R. G., Integrated global system model for climate policy assessment feedback and sensitivity analysis. *Clim. Change*, 1998.
17. Rupa Kumar, K. *et al.*, High-resolution climate change scenarios for India for the 21st century. *Curr. Sci.*, 2006, **90**, 334–345.
18. Palanisamy, K. M. and Gomez, K. A., Length and width method for estimating leaf area of rice. *Agron. J.*, 1974, **66**, 430–433.
19. Gomez, K. A. and Gomez, A. A., *Statistical Procedure for Agricultural Research*, John-Wiley and Sons Inc., New York, 1984, p. 680.
20. Mandal, B. K., Sainik, T. R. and Ray, P. K., Effect of age of seedlings and levels of nitrogen on the productivity of rice. *Oryza*, 1984, **21**(2), 232–252.
21. Kim, H. R. and Young, H. Y., CO₂ concentration and temperature on growth, yield and physiological responses of rice. *Adv. Biol. Res.*, 2010, **1**(2), 48.
22. Horie, T., Crop ontogeny and development. In *Physiology and Determination of Crop Yield* (eds Boot, K. J. *et al.*), American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, Wisconsin, 1994, pp. 153–1804.

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