Low-cost facility for assessing impact of carbon dioxide on crops

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A low-cost free-air carbon dioxide enrichment (FACE) system has been developed at the Indian Agricultural Research Institute, for assessing the climate change impacts on crops. In the FACE system, the supply and monitoring of CO_2 is regulated by the computer-based SCADA system. Carbon dioxide concentration recorded at 5 min intervals varied from 507 to 559 ppm in an hourly period. Monthly mean values of CO_2 concentration inside the ring ranged from 525 to 553 ppm from July to April. Crops grown inside the FACE ring showed increased yield over ambient CO_2 condition. The operating cost of the system is US\$ 100 m^{-2} yr^{-1}, which is much less compared to similar set-ups in other countries.

Keywords: Carbon dioxide, climate change, crop productivity, free air carbon dioxide enrichment.

IN the 20th century anthropogenic activities have caused excessive emission of greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) into the atmosphere, contributing to global warming and climate change. The global atmospheric concentration of CO_2 increased from a pre-industrial value of about 280–389 ppm in 2010. Annual CO_2 concentration growth rate was larger during the last 10 years (1995–2005 average: 1.9 ppm/yr) than it has been since the beginning of continuous direct atmospheric measurements (1960–2005 average: 1.4 ppm/yr)[1]. Over the last 100 years global temperature has increased by 0.74°C. The recent report of IPCC[1] has reconfirmed the increasingly strong evidence of global climate change and projected that the globally averaged temperature of the air would rise by 1.8–6.4°C by the end of the century, depending upon the developmental pathways of the countries. Primary effects of increased CO_2 on crops include higher photosynthetic rate, increased light-use efficiency, reduction in transpiration and stomatal conductance and improved water-use efficiency[2]. On the other hand, biomass and yield tend to decline with increasing temperature due to shortening of crop duration and lesser period of radiation interception[3]. However, it is a major challenge to evaluate the impact of rising CO_2 and temperature on crop productivity in the ambient condition.

Since future environment needs to be simulated, most of the studies on impact of elevated CO_2 on crops are based on controlled environment or enclosures like greenhouses, controlled chambers and open-top chambers[4,5]. The results of these experiments have been reviewed by several workers[5–7]. The environment inside these small chambers, however, varies from the open, natural field conditions and has serious limitations in terms of their small size, reduced radiation, restricted air flow, change in humidity and microclimatic conditions affecting plant growth and physiological processes. Chamber-effects have been very large in some cases[8] and there have been concerns that the results obtained from such enclosure-based CO_2 enrichment systems might not be representative of open-field conditions.

Free-air carbon dioxide enrichment (FACE) experiments allow studying the effects of elevated atmospheric CO_2 on plants grown under natural conditions[9]. In this system CO_2-enriched air is released into the ambient environment without causing appreciable changes in other environmental variables. Early types of FACE systems were built in The Netherlands[10] and UK[11,12] for exposing short-stature vegetation to elevated concentrations of atmospheric trace gases like ozone (O_3) and sulphur dioxide (SO_2). In India, impact of elevated CO_2 on rice crop grown inside the FACE ring was studied[13]. The most sophisticated FACE system was designed by Brookhaven National Laboratory's FACE Group, which employs computer regulation of CO_2 concentration in the FACE rings[14]. But the systems had serious constraint in terms of the high installation and operational cost involved in setting up these facilities in agricultural fields. Such high cost of FACE technology restricted its large-scale use, particularly in the developing countries with limited funds for research. Although annual operating cost of the FACE systems is about three times the cost of field chambers, FACE plots are relatively large leading to an economy of scale[15]. However, there is an urgent need to develop a automated, low-cost FACE system for assessing climate-change impacts on crops for wide and large-scale use. The objectives of the present study were to: (1) develop low-cost FACE system with high precision and accuracy and (2) assess performance of these low-cost systems in maintaining desired CO_2 concentration in ambient condition during two major cropping seasons (July–October and November–April) of India.

FACE ring: A typical FACE is a circular array of vertical or horizontal pipes that release CO_2 or air enriched with CO_2 to the crop canopy (Figure 1). The system we developed consists of a ring (plenum) made up of eight horizontal polyvinyl chloride (PVC) pipes each with a length of 2 m and diameter of 20 cm (arm). The diameter of the ring is 8 m. These pipes arranged in octagonal shape, were placed on a height-adjustable stand at 40 cm

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interval up to 1.20 m. Each arm of the plenum was fitted with centrifugal air-blower at one end, whereas the other end of the pipe was closed. In order to disperse the air, the pipes were perforated with holes of 3 mm diameter facing the innerside of the ring. Holes were placed at equidistance in three rows with one set of holes parallel to the treatment plot and the other two rows at 40° apart (Figure 2). Each pipe was connected to a solenoid valve (Fluidtecq Pneumatics, India).

Sensors: The FACE ring has temperature and humidity sensors fitted with transmitters and weather shielding. The sensor used for measurement of temperature was resistance temperature detector (RTD) type and the resistance material used was platinum. The humidity sensor is a solid-state capacity-type sensor. Sensors record ambient air temperature and humidity at regular intervals. Range of operation of temperature sensors was –40°C to +50°C, with resolution of 0.1°C. Humidity sensor operated at a temperature range of –40°C to +50°C, with a humidity range of 0–100%. Accuracy of this sensor was ± 3% of full-scale reading. Apart from these, wind speed and direction were measured at a height of 2.40 m in the same plane by a sensitive three-cup rotor anemometer and wind vane. The anemometer measures wind speed at 0–60 m s^{-1} range. Wind direction was recorded in degrees from north and wind speed in m s^{-1}. Output of both wind vane and anemometer was converted into current signals and was read out in a three-digit LED (light-emitting diode) display.

CO_2 supply system: The CO_2 supply system consists of CO_2 storage cylinders, CO_2 manifold, pressure guage regulator, flow meter, compressor, mixing chamber and solenoid valves. CO_2 was stored in CO_2 cylinders. Five cylinders were connected to a manifold system. Each cylinder was filled with 30 kg liquefied CO_2 (concentration 99.9%). From these cylinders CO_2 was released through a manifold system which was connected to a pressure gauge regulator operating at a pressure of 5 kg cm^{-2}. The CO_2 release path had a flow meter with range of 1–30 l min^{-1}. The pipe from the flow meter went to a mixing chamber. An independent compressor (capacity 100 l) was also connected to the mixing chamber for releasing the air.

Figure 1. Free-air CO_2 enrichment system in Indian Agricultural Research Institute, New Delhi.

CO_2 monitoring system: For monitoring CO_2 concentration inside the FACE ring, the air sample was sucked from three points (centre, 1 m and 2 m from the centre) in the FACE ring, through a pipe which was attached to a pump (1 HP) and routed through four glass columns containing silica gel (mesh size 4–6 mm), which were fitted between the pump and the infra red gas analyser (IRGA).

Concentration of CO_2 was measured by microprocessor-based non-dispersive IRGA, with a single-beam optical system (model ZRJ). Its range of operation was 0–2000 ppm. The IRGA was connected to a computer through the RS232 port. The computer was connected to an indigenously developed control system with ARM processor (Advanced RISC Machines Ltd, UK) and Supervisory Control Data Acquisition (SCADA) software that was integrated into the modular system consisting of 32 analogue input channels, 8 analogue output channels, 64 digital input–output channels and LED display for each FACE ring. The software was programmed in Visual Basic (VB). The computer-based control system regulates the functioning of solenoid valves and integrates with CO_2 concentration, wind direction and velocity.

Data logging: CO_2 concentration measured by IRGA was logged automatically in the computer at every 5 min interval. Data on temperature, relative humidity, wind speed and direction was also logged in the computer. The PC had the basic configuration with UPS having 30 min back-up for uninterrupted data storage. SCADA software inside the PC enables us to set the desired CO_2 level, minimum and maximum wind speed at which the release and cut-off of CO_2 supply should take place, as well as the time interval for data logging. The software displays the number of rings, humidity, air temperature and CO_2 concentration of each FACE ring along with wind speed. It also indicates direction of the wind and number of vent pipes which are open and releasing CO_2 into the FACE ring.

When the FACE system was switched on, the air was sampled from three points inside the FACE ring through a pipe. The sucked air was passed through the silica gel columns which removed the moisture from the air before being drawn into the IRGA at 0.6–1 l min^{-1}. The IRGA measured CO_2 concentration in the air and transmitted it to the computer. The CO_2 concentration was further communicated from the computer to the control system. Simultaneously the control system also received data on wind speed and wind direction as measured by the sensors, wind vane and anemometer. Integrating this information, the system regulated CO_2 release for maintaining the desired level of CO_2 inside the rings. For this, the SCADA software has a provision to set the minimum level of CO_2 concentration below which CO_2 is pumped and a maximum level above which pumping of CO_2 is stopped. If CO_2 concentration inside the FACE ring is less than the set value, the system actuates opening of the three solenoid valves located upwind of the FACE plot as

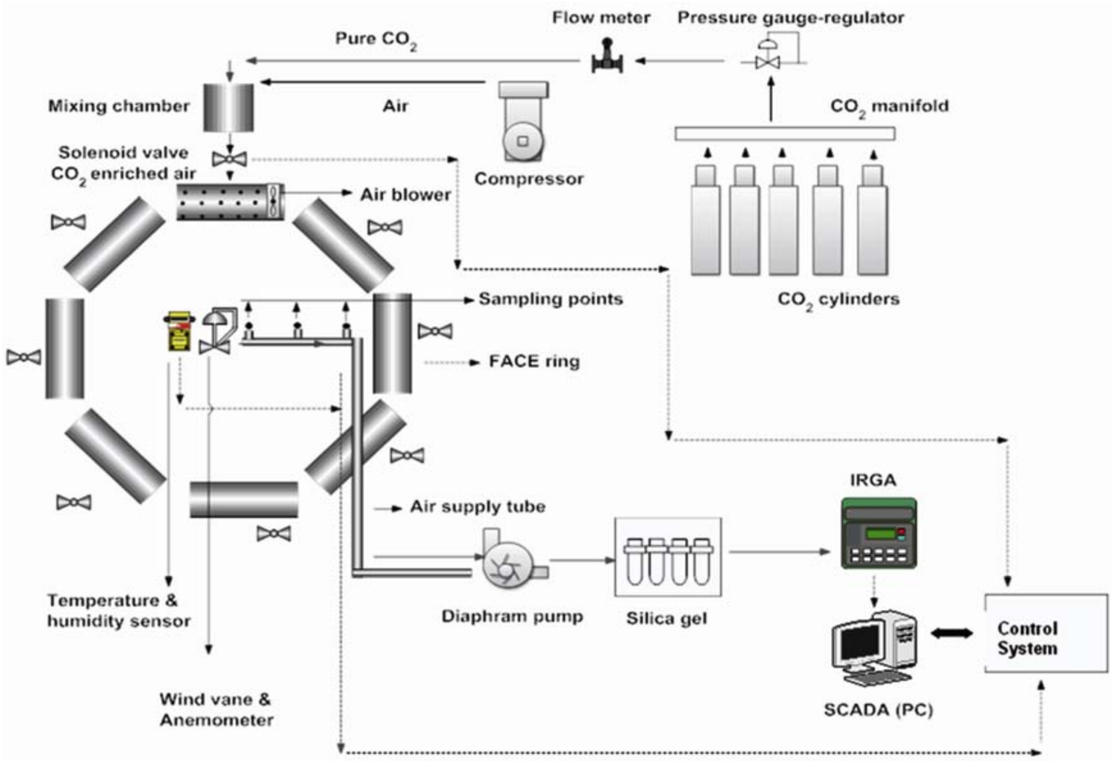

Figure 2. Schematic design of the FACE system.

a function of the most frequent wind direction. Opening and closing of the solenoid valves in the rings are regulated by the speed and direction of the wind. Under low wind conditions, it is difficult to determine wind direction and actually wind direction can rapidly fluctuate; therefore if the wind speed drops below 1 m s^{-1} for 60 s, directional control is terminated and every vent pipe around the FACE ring is opened. In high wind speed conditions (above 5 m s^{-1}) for 60 s, the directional control is terminated and every vent pipe around the FACE ring is closed. Once CO_2 level reaches the maximum set value (575 ppm), all the valves get closed automatically. Valves reopen when CO_2 level drops below the minimum concentration (550 ppm) set in the computer.

Pure CO_2 stored in cylinders connected to the manifold system, release is through the pressure gauge regulator to the mixing chamber. Flow meter was set between the regulator and mixing chamber for finer calibration of CO_2 release. Through another pipe air comes from the compressor to the mixing chamber. Before injection, pure CO_2 was mixed with ambient air coming from the air compressor in the mixing chamber. Level of dilution was determined during commissioning of the facility by regulating CO_2 injection flow rate. CO_2 gas was supplied through copper tubing and solenoid valves regulated CO_2 supply inside the FACE ring.

The FACE ring allows regulated delivery of CO_2 through an octagonal arrangement of horizontal, perforated pipes. The system relies on natural wind to disperse CO_2 across the experimental area and allows good temporal and spatial control of CO_2 concentration throughout the canopy[16]. This system has the provision of releasing CO_2 near the canopy for crops of varying heights. The air blower inside the arm of the plenum allows circulation of large volumes of CO_2-enriched air. Each arm of the plenum has independent CO_2 injection system and CO_2 enriched air is released through the small holes on the pipe near the crop canopy. Height of the ring was adjusted according to the height of the crop in order to release CO_2 at the canopy level.

The computer stored data recorded using sensors in Excel format indicating current CO_2 concentration in ppm, temperature in °C, humidity in % of each FACE ring along with wind direction (degrees from north) and velocity (m s^{-1}) at a duration of 5 min. This logging period can be set according to the requirement.

During commissioning, CO_2 concentration in the FACE ring was measured at different locations using portable CO_2 analyser and CO_2 flow rate was adjusted till CO_2 concentration in the entire FACE ring was within <10% of the target concentration.

The IRGA was regularly calibrated every 7 days at zero CO_2 level using pure nitrogen (N_2) gas and calibrated once a month with known concentration of CO_2. The FACE system was set up in the farm of the Indian Agricultural Research Institute (IARI), New Delhi to study the impact of elevated CO_2 on different crops. Every day the system was run for 10 h (8 a.m. to 6 p.m.) during daytime with auto injection of CO_2 to the canopy of crops grown in the FACE ring. As elevated CO_2

influences mainly photosynthesis in the presence of sunlight, the elevated CO_2 level was maintained inside the ring during daytime. Desired CO_2 level was set at 550 ppm. Data on CO_2 level and other parameters inside both the rings were recorded at 5 min interval. Variation in CO_2 level from the point of injection to the centre of the rings was monitored using portable CO_2 analyser at weekly interval. In this communication we have described the performance of FACE in terms of maintaining the desired CO_2 concentration inside the ring during crop growth.

The FACE system was run from July to April for 10 h daily. The system was able to maintain the desired CO_2 level inside the ring. Results discussed here describe the short, medium and long-term fluctuations in CO_2 concentration inside the FACE ring.

Short-term fluctuations in CO_2 concentration were monitored by recording CO_2 level inside the FACE ring during 10–11 a.m. on different days of the year varying in wind velocity (Figure 3). Average CO_2 concentration (logged at 5 min interval) inside the FACE ring varied from 507 to 559 ppm in an hourly period. Fluctuation in CO_2 concentration was due to the fact that the minimum and maximum values set in the system were 550 and 575 ppm respectively. Opening and closing of the valves caused rise and fall in CO_2 concentration and helped maintain higher CO_2 concentration inside the rings.

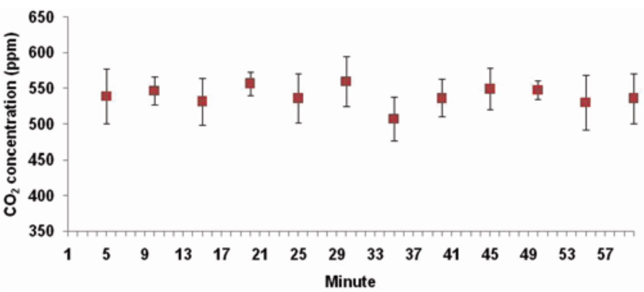

Figure 3. Carbon dioxide concentration in the FACE ring within an hour/period (recorded at 5 min interval).

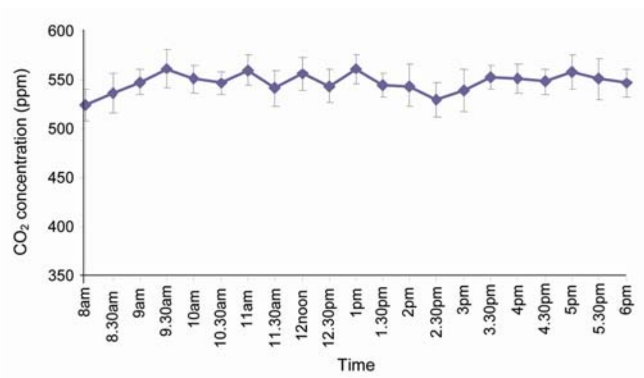

Figure 4. CO_2 concentration in the FACE ring recorded at half hourly intervals during a day.

In a day half hourly CO_2 concentration inside the ring varied from 525 to 562 ppm (Figure 4). The CO_2 concentration was the mean value for the same time-period (8 a.m. to 6 p.m.) for different days of a year. Fluctuations in CO_2 level were noticed due to the varying wind speed on different days.

Daily values (medium-term) of CO_2 concentration for July were correlated with daily wind speed to understand the effect of wind speed on the functioning of the FACE system. July month was selected because the month is windy. Wind speed during this month varied from 0.1 to 4.44 m s^{-1}. CO_2 level was within 10% of the target (550 ppm) during 62–82% of the time (Figure 5). Deviation was more under high wind speed conditions. Carbon dioxide concentration inside the ring remained within 10% of the desired level (550 ppm) for maximum time (82%) when mean wind speed was 0.81 m s^{-1}. This shows that less wind speed helps in maintaining CO_2 level inside the FACE ring, whereas higher wind velocity dissipates the CO_2 released through the pipes resulting in low CO_2 concentration and more loss of CO_2 in the ring.

Long-term control of desired CO_2 concentration inside the FACE ring was quite satisfactory. Monthly mean values (long-term) of CO_2 concentration inside the rings during 10 hourly period of its operation indicated that desired CO_2 level was maintained inside the ring from July to April. Mean values of CO_2 concentration during this period ranged from 525 to 553 ppm (Figure 6). Error bars indicate the fluctuations in CO_2 level within a month, which were attributed mainly to varying wind speed on different days of a year. An experiment conducted in the FACE facility at the University of Arizona, USA, also showed that CO_2 concentration was controlled at its targeted level at the centre of experimental plot just above the canopy[17].

Distribution of CO_2 inside the ring showed decline in CO_2 level from the periphery to centre of the FACE ring. Mean values of CO_2 concentration at different points inside the ring during the cropping season indicated that CO_2 level near the perforated pipes (the release points)

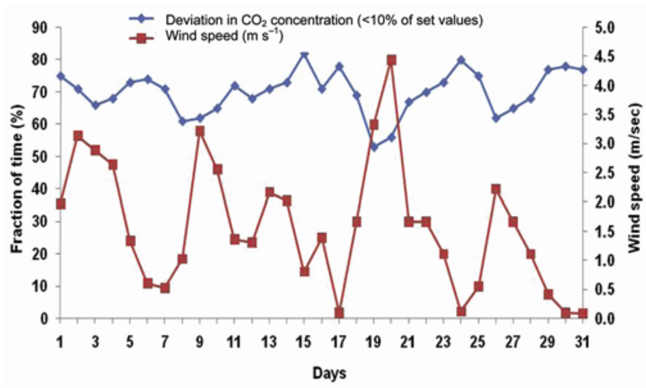

Figure 5. Deviation in CO_2 concentration (<10%) in both the rings in July.

was maximum. Mean CO_2 level on both side of the rings was 585 ppm, whereas at the centre it was 542 ppm (Figure 7). This showed that CO_2 concentration inside the ring varied by 7.9% from the periphery of the pipes to the centre. This variation has less impact on photosynthesis of crop plants. Sampling point of CO_2 was near the centre of the ring. So data recorded by the system was CO_2 concentration near the centre of the ring, which was 43 ppm less than that in the injection point. Spatial uniformity of CO_2 concentration inside the ring was attributed to its diameter which was not very large (8 m) and the blowing wind which helped in rapid diffusion of CO_2 inside the whole ring. The CO_2 distribution in similar studies also showed a decline in concentration from the concentrated CO_2 at the outlet to 443 ppm at the centre and to 407 ppm at the far side of the octagon[18].

The FACE developed in IARI is being used to quantify the effect of increased CO_2 on crop plants. Some studies revealed that under high CO_2 condition, the yield of crops increased substantially compared to ambient CO_2 level. Grain/seed yield of greengram, soybean, chickpea and wheat crop increased by 10.9%, 15.8%, 21.1% and 16.7% respectively, in CO_2 treated plots over ambient CO_2 treatment (Figure 8).

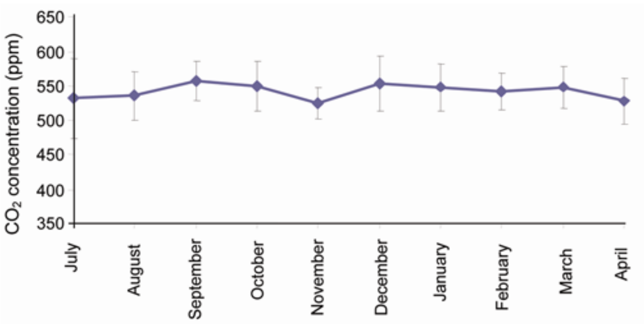

Figure 6. Monthly average CO_2 concentration inside the FACE ring in 2007.

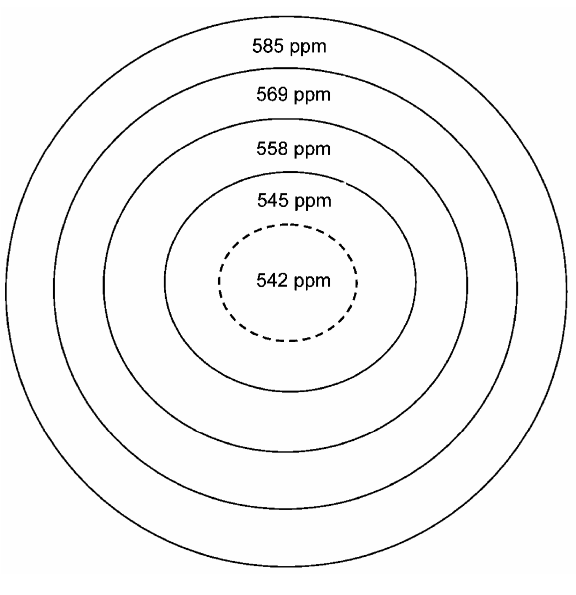

Figure 7. Distribution of CO_2 (ppm) inside the FACE ring at 1 m interval.

Expenses involved in this system include both capital and operating costs. The cost of installing a FACE ring was US\$ 50,000. Operating cost of the system included expenses on CO_2, electricity and maintenance (Table 1). One CO_2 cylinder per FACE ring was used for 2 days, when pumped only during daytime. Maintenance cost included cost of N_2 cylinder, for calibration, silica gel and cost of labour. Electricity was required for running the compressor, pump, air-blower, IRGA, PC and the air-conditioning system of the control room. Apart from this, the system requires 8 h of a single manpower every day for its operation and maintenance. Computing all these costs, the operating cost of the FACE system was found to be US\$ 5000/yr, i.e. US\$ 100 m^{-2} yr^{-1} (Table 1). Earlier workers have reported that the major limitation for the FACE technology is the cost involved in running this system[19]. This cost varies with location and environmental factors. Expenses involved in operating the FACE system in IARI were compared with other systems working in USA, Italy and Switzerland (Table 1). For comparison, the cost of operation in all the experiments was calculated for one year, assuming that the FACE system in all experiments worked for 365 days a year. In the four experimental set-ups (two in USA and one each in Italy and Switzerland), CO_2 level ranged from 550 to 600 ppm and ring diameter varied between 8 and 25 m. Total annual operational cost (US\$ m^{-2}) was maximum in the Potato FACE experiment in Italy. The operation cost in the present study was only more than the AZFACE experiment of USA. This might be due to cost escalation, as the AZFACE experiment of USA was 16 years older than the present study. Comparison with three other FACE experiments in USA, Italy and Switzerland showed that the annual operating cost per unit area for this set-up was 7–75% less. This was due to less cost of CO_2, electricity and less maintenance cost in the FACE set-up under the present study. Apart from these, the local

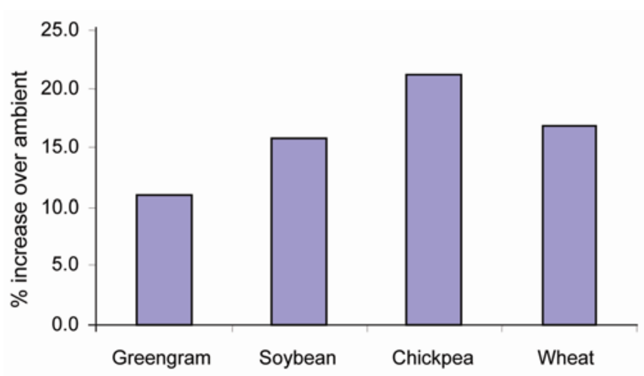

Figure 8. Increase in grain/seed yield of selected crops grown inside the FACE ring.

Table 1. Operating cost for free-air carbon dioxide enrichment experiments in different countries

Project	Country	Ring diameter (m)	CO_2 level (ppm)	Annual costs ('000 US$)				Operation cost (US$ m^{-2} yr^{-1})	Reference
				Cost of CO_2	Electricity	Maintenance	Total operation cost		
AZFACE	USA	25	550	30	2	8	40	81	17
SoyFACE	USA	20	550	20	3	11	34	108	20
Potato FACE	Italy	8	560	7	3	10	20	398	14
Swiss FACE	Switzerland	18	600	38	1	1	40	157	21
IARI-FACE	India	8	550	2.6	1.0	1.4	5.0	100	Present study

wind turbulence, rains during cropping season and time of CO_2 injection might have also contributed to the variability in running cost. Thus, this indigenously developed FACE system can be used as a low-cost intensive alternative to other FACE systems.

The FACE system described here was designed to conduct climate-change experiments at field level by maintaining the desired level of CO_2 at low installation and maintenance costs. A major benefit is that the system is automated. The system was able to maintain desired CO_2 concentration (550 ppm) at short-, medium- and long-term scale. CO_2 level maintained in the FACE rings was almost uniform with very less CO_2 gradient. Experimental studies showed response of field crops in terms of enhanced yield inside the FACE system. Cost involved in operating the system was substantially less than similar set-ups in other countries. Efforts are being made to overcome the limitations and develop corrections factors to account for the impact on crop growth and yield. This low-cost FACE system has good potential for wider application to study the impact of climate change on different crops.

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