

Carbon dioxide enrichment technologies for crop response studies

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Received 05 April 2006; accepted 20 July 2006

In recent years, a number of technologies have been developed to study the impact of rising atmospheric CO₂ in agricultural systems. Earlier techniques were based on the controlled environment such as phytotrons, closed chambers, cuvettes etc, which are far from the natural environment, in which plants generally grow. However, technologies such as FACE (Free Air CO₂ Enrichment), OTCs (Open Top Chambers) and SPAR (Soil Plant Atmosphere Research) with holistic approach have been developed and are being currently used for crop response studies. South Asian Mid FACE and open top chambers are such holistic technologies, developed at Indian Agricultural Research Institute (IARI), New Delhi, for crop response studies under natural field condition. The data base generated using these facilities will be more realistic for impact assessment analysis of the rising atmospheric CO₂ on crop plants and for developing models to predict responses for future climatic conditions.

Keywords: CO₂ enrichment technology, Free air CO₂ enrichment, Open top chambers, Soil plant atmosphere research, South Asian Mid FACE

IPC Code: A01C3/00

Introduction

Global climate changes caused by anthropogenic green house gases will no doubt affect food productivity directly and cause concern for food security indirectly as the population increases. Since the industrial revolution, the combination of fossil fuel burning and deforestation has led to an increase of carbon dioxide (CO₂) concentration (26%) in the atmosphere¹. CO₂ concentration is predicted to double by the middle of next century if the CO₂ injection rate is left unabated. Being major determinants of crop growth and development increased atmospheric CO₂ and temperature can have significant impacts on the productivity of agro ecosystems².

Most of the researches on plant responses to high CO₂ have been conducted under laboratory, greenhouse or controlled field conditions³. Agricultural scientists have used controlled environments and field based facilities to study the crop responses to radiation, temperature, humidity and water availability⁴. Technologies, used earlier based on single component approach have been

successfully applied to study the responses of plants to increased CO₂. Although this single component approach is highly effective way of discovering how one atmospheric factor influences crops, in practice, several interactions will affect the responses. Results obtained with isolated plants growing under controlled growth conditions, life phase synchrony, absence of organism interactions and provision of luxurious amounts of mineral nutrients appear to be the major limitations for the application of results of a large number of CO₂ enrichment studies.

Before 1980, most studies on the effects of elevated CO₂ were carried in controlled environmental facilities including leaf cuvettes, whole plant growth chambers and greenhouses. There are extensive, precisely controlled closed systems that continuously recondition and recirculate the air in controlled environment of growth cabinets, phytotrons, and open field exposure systems, such as Free Air CO₂ Enrichment (FACE), which is moderately more expensive and less precise than closed systems. During current decade, new approaches to CO₂ enrichment have potentially reduced the costs. Improved experimental design can help to characterize temporal dynamics of ecosystem carbon processes. Currently, most of the CO₂

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experiments using enrichment facilities follow a holistic approach to design experiments in ecosystems as natural as possible and then to observe their responses.

CO₂ Enrichment Technologies

A number of CO₂ enrichment technologies have been developed so far as follow:

(A) Leaf Cuvettes (LCs)

LCs are designed for single leaf gas exchange measurements and can be used for measuring gas exchange as a part of system for studying the short time effect of elevated CO₂ levels on the CO₂ exchange processes in leaves. LCs are of two types:

(1) Open Exhaust System

Air of known composition is passed over the leaf and change in CO₂ and water vapor caused by the leaf is determined. These help in determining the photosynthesis and transpiration rates. Sinclair & Horie⁵ used cuvette system with an infrared gas analyzer (IRGA) to measure the drop in CO₂ content of air passed through leaf.

(2) Closed Circulation Systems

In these chambers, null balance approach is used and the change in CO₂ and water vapor in the chamber is determined from the rate of injection of CO₂ and H₂O required to maintain a set point. Sinclair *et al*⁶ designed these leaf cuvettes for CO₂ exchange studies. Cuvette consists of two disks of clear teflon separated by a pair of chrome-plated brass rings. Leaf is inserted between rows of monofilament line in each ring. Leaf temperature is controlled to ambient temperature through a water jacket in the rim of the chamber. Allen⁷ used this system for studying long-term responses of soybean leaves to elevated CO₂.

(B) Sunlit Controlled Environment Chambers (SCEC)

These chambers usually had Mylar polyester film walls and were used successfully for measuring photosynthesis and transpiration as a function of CO₂ concentration, light, temperature and soil moisture conditions. These systems were the predecessors to the units with large controlled root-zone containers as well as canopy zone chambers⁸.

(C) Soil Plant Atmosphere Research (SPAR)

SPAR chambers were designed to provide accurate, flexible control of dry bulb temperature, CO₂ concentration and humidity of the canopy air, as well as control and measurements of soil water and

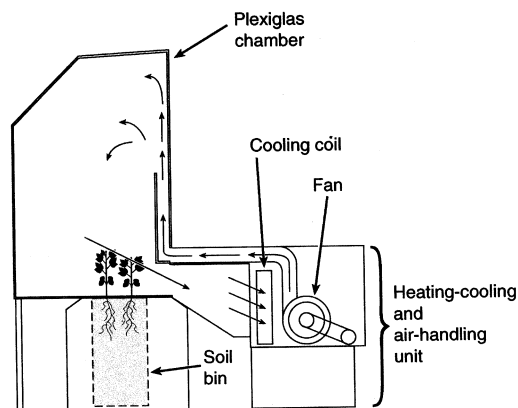


Fig. 1 — Diagrammatic presentation of soil plant atmosphere research (SPAR) System

root conditions. Jones *et al*⁹ designed these units by modifying the facilities developed by Phenix *et al*⁸ for CO₂ enrichment studies.

SPAR system consists: 1) Sensors for measuring temperature (copper-constantan thermocouple); 2) IRGA for sensing CO₂; 3) Dew point hygrometers for measuring humidity; and 4) Control devices such as heaters to regulate desired temperature. CO₂ injection valves for measuring CO₂ used in photosynthesis and cooling coil flow for regulating dew point temperature are incorporated in SPAR system (Fig. 1). Air in these SPAR chambers was circulated through the canopy from top to bottom and then goes out through ducts, where it was reconditioned before flown back to the canopy chamber. Sensors, air sampling ports and control devices were located within the ducts so that the air circulated to the top of the canopy had the experimentally prescribed set point of temperature, CO₂ concentration and humidity level.

Advantages of SPAR system are: A) High light, similar to natural irradiance; B) Variable conditions; C) Provides continuous integrated measurements of CO₂ and H₂O balance; D) Root zone similar to field; and E) Control to specified set points or track ambient environment, temperature and humidity. Disadvantages of SPAR are: A) Complex control, chamber effects (humidity, wind gradients); B) Limited replications; and C) Expensive cost per unit.

(D) Portable Field Chamber

This technique has been applied to canopy photosynthetic CO₂ exchange measurements in subsequent studies. Non-dispersive IRGA (vol, 1.033 m³) covered with Mylar film was used for measuring CO₂. A 30 cm fan was used to circulate air within the chamber. The air was pumped through 0.6 cm

diam tube at 8 l min⁻¹ to IRGA to measure the photosynthesis rate and regulate CO₂ concentration in the chamber.

(E) Open Top Chamber

Open top chambers (OTCs)¹⁰ were extensively used as plant exposure units both in air pollution and in CO₂ response studies in the field. OTCs, which have been used to expose potted plants, annual crops and trees to a variety of aerial pollutants and CO₂, are currently in use at a number of laboratories in North America, Europe and South Asian countries. Hardy & Havelka¹¹ first used a square walled open top enclosure to expose soybeans to atmosphere enriched with CO₂ for studying the effect of increased photosynthate production on symbiotic nitrogen fixation. Rogers *et al.*¹² adapted basic cylindrical OTC system to generate large-scale CO₂ test atmospheres in the field. Nakayama & Kimball¹³ used a square wall OTC (diam, 0.2 m) perforated polythene rows for cotton. Drake *et al.*¹⁴ developed an OTC system for CO₂ enrichment of salt marsh vegetation that re-circulated part of input air. Uprety *et al.*¹⁵ designed and developed OTCs for South Asian climatic conditions. These chambers with frustum are being used by South Asian CO₂ research network for multi country multi disciplinary CO₂ crop response studies.

Uprety¹⁶ described the South Asian OTC technology with 5 sub systems: 1) Supply of pure and high concentration of CO₂; 2) System of valves, regulators and flow meters; 3) CO₂ controlled chambers; 4) Appropriate gas analyzer with feed back control; and 5) Computed data acquisition and programming. These OTCs (diam, 3 m) were made of an aluminum frame installed on the ground. Vertical sidewall was also 3 m in height and top of chamber was kept open to provide the near natural conditions. These chambers had a characteristic slender shape and were covered with a 0.15 mm thick transparent polyvinyl chloride (PVC) sheet. Chambers are equipped with a frustum at the top to deflect air and prevent dilution of the desired CO₂ concentrations within the chamber. There was a cylindrical double walled plenum around the base for uniform CO₂ circulation. Inner side of the plenum was provided numerous gas outlets of different sizes, small being nearest to the gas inlet pipe. Commercial CO₂ was added in the upstream of frame to ensure adequate mixing and to create the desired concentration. Blowers were used to distribute CO₂ enriched air uniformly throughout the plant canopy. CO₂ gas was

supplied to the chamber from gas cylinders using a manifold, gas regulators and pressure gauze pipelines. Gas cylinders were fitted in a row with thick copper outlet pipe. CO₂ gas was released from cylinders to chamber through a manifold and underground pipe and injected into the chamber along with the ambient air using a blower. Air blowers (diam, 30 cm) are used for maintaining desired concentration of CO₂ into chamber tunnel. Blower also helped in maintaining inside air temperature closure to that of outside ambient atmosphere. Relative photosynthetic photon flux density (PPFD) in the chambers was maintained about 95% of full sunlight by frequent and gentle washing of the transparent polythene sheet. Daily observations on temperature and relative humidity were monitored in the chambers and recorded in thermo hygrograph (Lawrence and Mayo, India model W/1712/Z). Weekly changes in chart paper of thermo hygrograph are recorded during cropping seasons. Diurnal variations in temperature, light intensity and CO₂ concentration inside and outside the chambers are recorded regularly (Fig. 2).

OTC is one of the most widely used techniques for studying elevated CO₂ impact on crops and ecosystems. Climate in OTC tracks the dynamic change in temperature, light, rainfall as experienced in unclosed area without costly and complex environmental controls characteristics of closed chambers. OTC subjects the whole plant to the treatment without restricting the root growth. The principal advantage of OTC is the ability to provide control over the atmospheric variations to which plants are exposed while maintaining more or less the same soil conditions of the field setting. There are several research needs to improve the OTCs as a field experimental tool. Fluid dynamics and heat exchange properties, particularly the effects of turbulence and altered flow path of wind within the canopy should be studied to determine potential effects of increased CO₂ on plant growth.

(F) Temperature Gradient Chambers (TGCs)

To study the interaction of temperature increase with elevated CO₂, Temperature Gradient Chambers (TGCs) were constructed for maintaining different CO₂ concentrations. Earlier TGCs (50 cm high, 10 m long) were plastic green house with an air inlet at one end and an exhaust fan at other end. TGC (3.6 m height x 18 m length) constructed as commercial green houses with steel pipes (diam, 19 mm) were covered with 0.1 mm thick UV transparent PVC film.

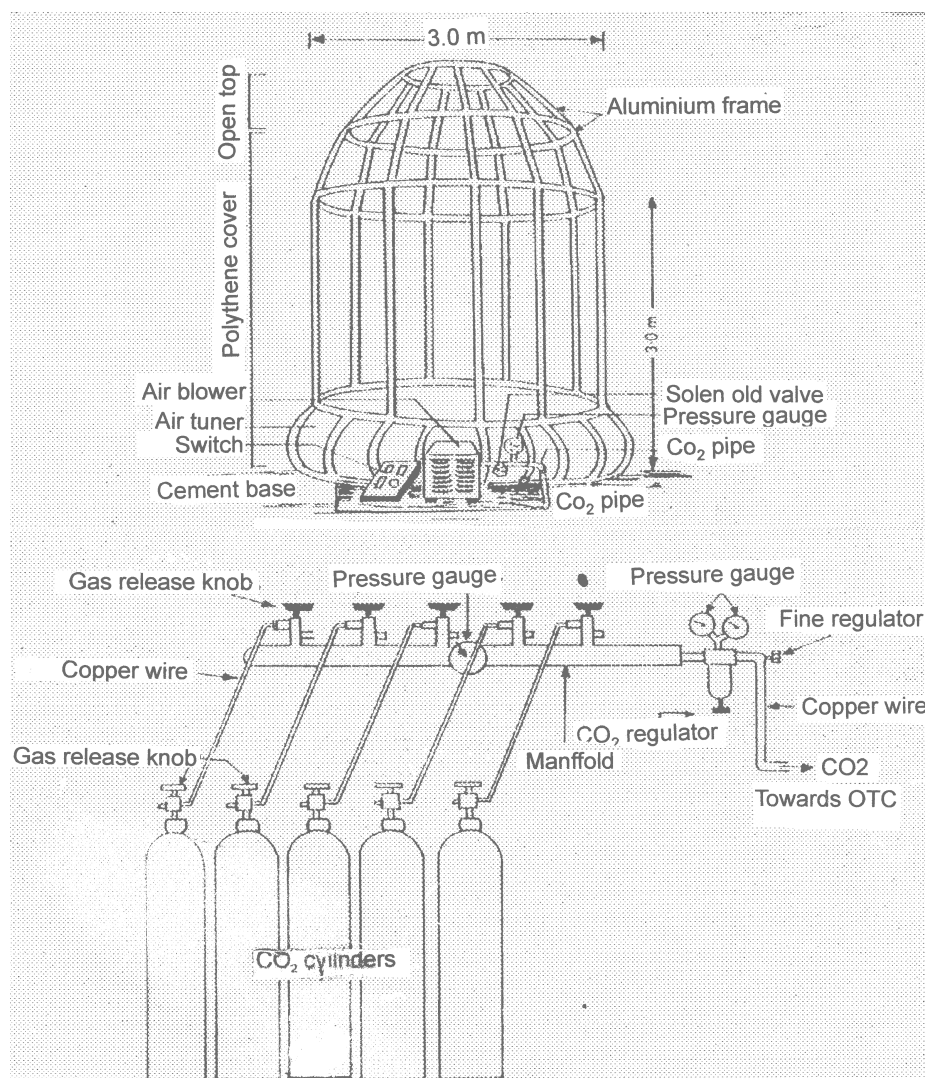


Fig. 2 — Open Top Chamber and its CO₂ regulating system

TGC was in north south orientation to obtain fairly uniform spatial distribution of direct solar beam in summer and to minimize the influence of shading of neighboring chambers in winter. Light transmittance observed under clear sky was: July, 77; and November, 66 %. Perforated panels were used as air inlets to regulate incoming air flow. Three exhaust fans (ventilation capacity of each fan, $28 \text{ m}^3\text{min}^{-1}$) were installed at other ends. TGCs ($2.45 \text{ m} \times 1.25 \text{ m} \times 1.25 \text{ m}$)^{17,18} were designed to grow wheat to study the responses of specific genotypes to variable temperature and CO₂ concentrations. TGCs were covered with 6 mm UV stable polythene sheet. Outlet plenum was a box ($0.65 \text{ m} \times 1.25 \text{ m} \times 1.25 \text{ m}$) covered with PVC sheet. Fan was mounted on the roof pointing outwards. This film is elastic and

reduces the damage of water and hail. Temperature difference between inlet and outlet doesn't go more than 5°C. Temperature measured by differential thermocouples was used to set the required fan speed electronically. CO₂ concentration was continuously monitored at the outlet fan by an IRGA. Airflow needed to maintain temperature gradient (Fig. 3) was sufficient to prevent any measurable difference in CO₂ concentration between modules ($10 \mu\text{mol mol}^{-1}$).

(G) Carbon dioxide-Temperature Gradient Chamber (CTGC)

CTGCs ($2.5 \text{ m} \times 3 \text{ m} \times 30 \text{ m}$) are made of semi circular pipe coated with zinc. UV transparent PVC film, through which 85 % radiations of 250-700 nm passes, was used to cover these chambers. Air in chamber was heated by solar radiation. However, at

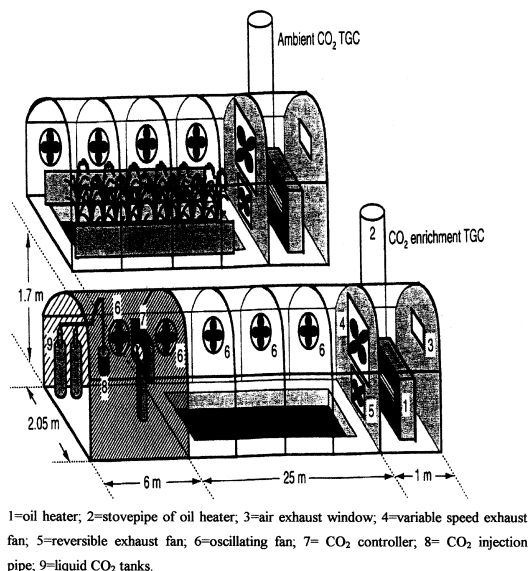


Fig. 3 — Schematic drawing of the temperature gradient chamber (TGC) for CO₂ enrichment (bottom) and ambient CO₂ (top) developed at Kyoto, Japan¹⁷

low radiations, oil heaters were used. CO₂ was injected at a rate controlled automatically by an electronic mass flow controller. CO₂ (conc. 372, 537 and 756 $\mu\text{mol mol}^{-1}$, respectively at 0, 10 and 25 m away from the air inlet) was supplied through longitudinal pipe installed at 10 cm height along inside wall of CTGC. During night¹⁸, CO₂ concentration was higher due to respiratory CO₂ from plants and soil.

(H) Screen-aided CO₂ Control (SACC)

SACC is a novel CO₂ exposure system for natural vegetation. It ameliorates microclimate problems associated with OTCs and has lower operating cost per experiment. Each SACC unit consists of a hexagonal steel frame, a clear polycarbonate screen and an air distribution duct. Leadly & Drake¹⁹ used it to study grasslands of Switzerland. It was designed to increase the incursions of outside air for minimizing microclimate change in contrast to OTC. Screens were used to break the wind. CO₂ dispensing rates were highest during midday and lowest at night and there was a strong correlation between wind speed and CO₂ dispensing rate. However, active CO₂ control system was effective enough to maintain CO₂ concentration even in relative windy condition. CO₂ concentration at 25 cm above the ground shows that vegetation acts an important buffer against large deviations from the set point. Spatial control of CO₂ concentration is good within the vegetation, which

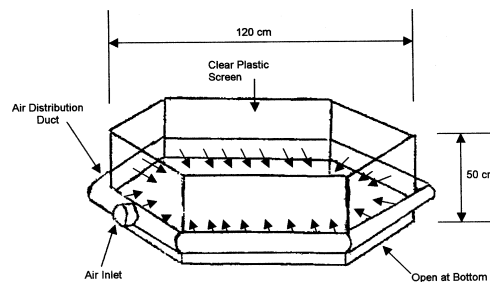


Fig. 4 — Screen aided CO₂ control (SACC) system¹⁹

comes from comparison of effects of elevated CO₂ on plant biomass in border and centers of SACC. Effect of microclimate is negligible in this facility. Air temperature difference is only 1 K (Fig. 4).

(I) Free Air CO₂ Enrichment Technology (FACE)

FACE system²⁰ provides a unique opportunity to examine the effects on plant growth at elevated CO₂ and other environmental conditions without any direct perturbation of microclimate. Development of FACE program had following objectives: A) To maintain sufficiently steady CO₂ concentration so that fluctuations in CO₂ cause no perceptible effect on plants grown within the environment; B) To provide reliable field data on the response of crops and other plant communities to develop and evaluate mechanistic plant growth models, which can contribute to predict the effects of future CO₂ concentration and climate changes on plant growth and water use; and C) To contribute for an evaluation of global CO₂ fluxes and carbon balances between vegetation and rising atmospheric CO₂. Maricopa FACE, the first such system developed in Arizona, had arrays of 32 vertical vent pipes, with each vent pipe containing multiple gas emitter ports. Each vent pipe in an array is connected to a common 22 m diam torridly distribution plenum through an individually controlled valve. The proportional integrative differential (PID) adjust the amount of gas in to the plenum and another algorithm considers both wind direction and speed and controls the vent pipes that emit CO₂ enriched air.

South Asian FACE

South Asian FACE²¹ is also based on the principle of injecting additional CO₂ in open field suitably so as to attain a predetermined elevated level of gas concentration with uniform distribution inside FACE ring under varying metrological conditions of wind, temperature and humidity. Main components of this facility are: 1) CO₂ storage and distribution system;

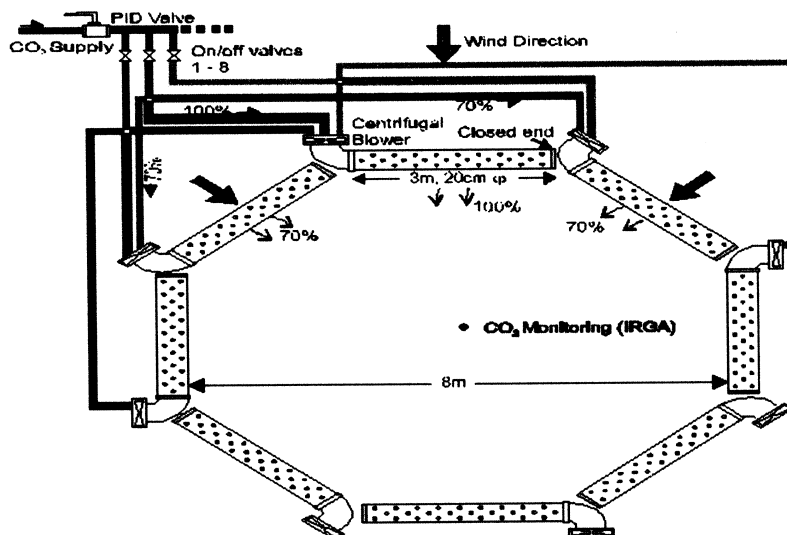


Fig. 5 — Octagonal ring of South Asian Free air CO₂ enrichment (FACE) technology

2) FACE ring (Plenum), through which CO₂ enriched air is injected into open field; 3) Different sensors and actuators used for monitoring the environment and controlling the operations; and 4) An electronic system for controlling these operations. CO₂ concentration was measured at the center of the array with the help of an IRGA. The PID valve controls quantity of CO₂ to be released in to plenum arms, which depends on the voltage (0-10 V) applied to it. To evaluate proper operation of PID valve, a feedback signal was also monitored to know the actual status of the valve. This signal (0-5 V) corresponds to the fully closed and fully open conditions of PID valve²².

Fumigation of CO₂ in to FACE ring from the plenum was made at the crop canopy height. The height of the plenum could be adjusted from time to time to match with the height of the crop canopy by resting the plenum on height adjustable stands. Plenum could be raised up to 150 cm from ground level in steps of 5 cm. Two banks of 25 cylinders in parallel were used for CO₂ storage and dissemination under constant pressure. A buffer tank was installed after the cylinder bank, which took care of the pressure variations in supply line due to decreasing level of CO₂ in the cylinders during Mid - FACE operation.

Control system measured in every second the data from meteorological sensors (wind speed and direction) along with CO₂ concentration. Based on these inputs, control system, through a specially developed PID algorithm, controlled flow rate of CO₂ in the plenum with the help of PID controller valve.

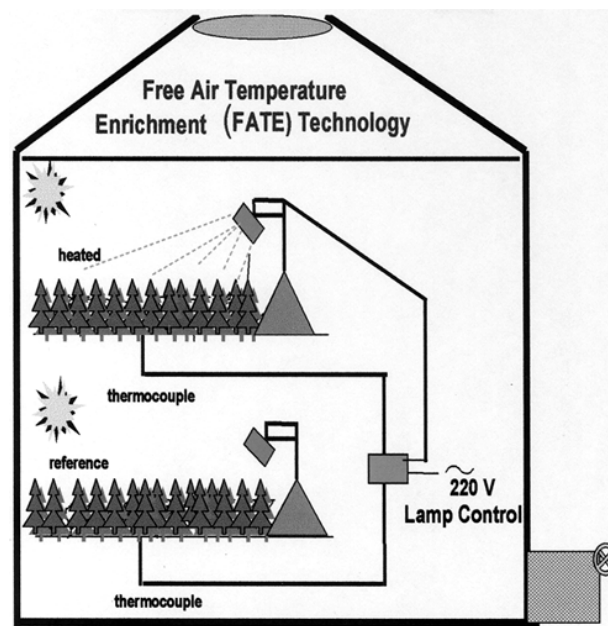


Fig. 6 — Temperature regulating system in open top chambers and FACE

Direction of wind decides which on/off valve was to be opened to release CO₂. In case the wind velocity was less than 0.5 m/s (which is taken as the case of calm air), valves were opened in a cyclic order as no dispersion of CO₂ occurs in such conditions. Thus a predetermined constant level of enriched CO₂ was maintained at the center of plenum. South Asian FACE is expected to include temperature enrichment device in future (Figs 5 & 6).

Table 1 — Advantages and disadvantages of CO₂ enrichment methods

CO ₂ enrichment methods	Advantages	Disadvantages
Leaf Cuvettes	Single leaf response study Specialized study on single factor approach	No whole plant response Low light Higher/ constant day night temperature Higher relative humidity
SPAR system	High light similar to natural condition Control of temperature and humidity	Chamber effects Higher temperature and relative humidity Wind gradients Limited replications Expensive per unit
CO ₂ temperature gradient tunnels	Suitable established CO ₂ and temperature gradients for interaction studies	Possible chamber effects Gradients may be variable
Open top chambers for South Asian region	<i>In situ</i> study on crops and natural vegetation Near natural environment Regulates elevated CO ₂	Gradients of wind and humidity produce chamber effects Many chambers need to deal with natural variability of agro eco systems
South Asian Mid FACE	Closed to natural environmental conditions Large area of plant material	Complex controls Large area needed Cost may be higher

(J) Free Air Temperature Enrichment Technology (FATE)

FATE components include two 1500-watt IR lamps (positioned at about 1.2 m above ground), which can homogeneously irradiate 40-50 cm path of vegetation at an angle of 40° above ground. These lamps are regulated by proportional action controller, which modulates IR flux density (frequency, 10 Hz) to obtain a preset target differential (T) between heated and a corresponding unheated plot. IR lamps, used in simulating temperature, are made of tungsten filament and can irradiate at 2000°C. Filter is used to selectively cut off visible light so that light can be continued in night. It also removes wavelength to which phytochrome is sensitive so that photomorphogenesis can be avoided. FATE irradiation²³ is uniform in space and time.

Conclusions

Different methods of enriching crops with CO₂ in the field have relative advantages, which must be considered in conjunction with costs (Table 1). Although expensive, free air enrichment is the best approach for gathering relevant data for assessing the impact of elevated CO₂ on crops, while OTCs are more amenable to the study of interactions with temperature. Future concentrations of atmospheric CO₂ can now be produced in OTCs and open field FACE. To stimulate anthropogenically induced climate warming on the other hand, techniques have recently become available. Addition of temperature

control system to open top chambers in the field adds an important component to the technology to the global climate change research.

While there are many studies on the response of plants, soils and ecosystems to rising atmospheric concentration of CO₂, interactive effects of elevated CO₂ and temperature needs to be fully explored in a natural field setting by developing technology associated with a CO₂ + temperature interaction effects. Combining Free Air Temperature Enrichment (FATE) technology with that of FACE needs to be explored for exposing agro ecosystems to the elevated CO₂ simultaneously with elevated temperature. New technologies based on series of microcomputer control systems for effective control of CO₂ concentration needs to be developed. An engineering synthesis of these technical advances with an understanding of the needs of biological experiments from concept of prototype to facilities is essentially required. It is important that these technologies demonstrate convincingly the extent of the inherent variability in their ability to control CO₂ concentration and to assure a high level of operational integrity. New FACE concept of producing CO₂ concentration gradient experiments are under development and progress is promising. With further engineering development and testing, more realistic and cost effective methods for elevated temperature and CO₂ experiments in open-air settings will be designed.

These technologies present a window into the likely future of ecosystem function in a CO₂ enriched warmer world. Despite some limitations, these sub natural CO₂ enrichment technologies are best approaches to realistic open-air field experiments.

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