CONTROL OF CO_2 INSIDE AUSTRALIAN GRAINS FREE AIR CARBON DIOXIDE ENRICHMENT (AGFACE) FACILITY

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Abstract The Australian Grains Free-Air Carbon dioxide Enrichment (AGFACE) facility was established at Horsham (36°45′07″S latitude, 142°06′52″E longitude), Victoria, Australia in 2007 to conduct research under Australian conditions with the aim to generate field response data in broad-acre wheat to elevated levels of CO2. Carbon dioxide concentrations within the rings in the AGFACE facility are computer controlled, using inputs of sensed carbon dioxide concentration, wind speed and direction at the centre of each ring. The control system uses a number of pneumatic valves and associated fittings driven by a control algorithm. On average, the control system at the Horsham site has enabled the AGFACE rings to maintain the concentration of CO2 at the centre of the ring at ≥90% of the target (ie. ≥495 ppm) for 97% of the operating time. The typical mean CO2 concentration at the centre of an AGFACE ring was 550 ± 28 ppm and this meets the generally accepted standards for defining FACE systems operating limits.

Keywords: spatial variation, climate change, CO2 meter, CO2 sampler, CO2 analyser

1. INTRODUCTION

A collaborative project between the Victorian Department of Primary Industries (DPI) and the University of Melbourne commenced in 2007 to establish the Australian Grains Free-Air Carbon dioxide Enrichment (AGFACE) facility. The main aim of the research is to generate field response data of field grown wheat crops to elevated levels of CO_2 (eCO_2) across a range of temperature and water supply conditions.

The AGFACE uses direct injection of CO_2 in the atmosphere and is based on the Brookhaven National Laboratory design (Lewin et al. 1994) similar to other systems such as Rice FACE (Okada et al. 2001) and POPFACE (Miglietta et al. 2001). In these systems, CO_2 is injected into the atmosphere on the upwind sides of an octagon around the target through 0.3 mm holes. In the process, CO_2 gas jets reach sonic speeds and create shock-waves at the jet outlets which enhance the mixing of CO_2 gas with air. This mixed air-CO_2 is then quickly transported across the ring by the prevailing wind. According to Hendrey et al. (1993) control of CO_2 concentrations within the FACE system should be within a criterion of ±20% for set point of 1-min averages at least during 80% of the experimental period. This is generally the accepted design criterion for FACE experiments (Okada et al. 2001; Hovenden et al. 2006).

This paper describes the major components used to maintain and control the target CO_2 concentration of 550 ppm within the protocol tolerance at the centre of an eCO_2 AGFACE ring and presents basic performance results for the control system used.

2. MATERIALS AND METHODS

The AGFACE facility consists of 1) a supply of CO_2 gas to the field from a bulk container, 2) power supply to each ring, 3) central control system for individual ring, 4) AGFACE rings, 5) CO_2 gas analyser, 6) wind sensors and 7) data monitoring and acquisition system (Fig.1).

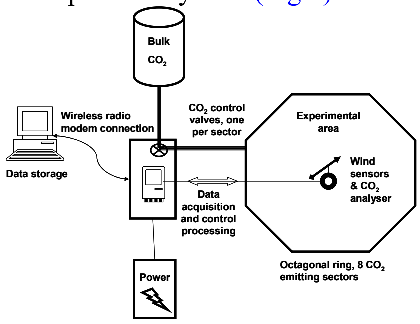

Fig.1. Diagrammatic representation of the elements in an AGFACE ring in the field.

The experimental system at Horsham consists of a 7.5 ha site with eight eCO_2 rings and eight control ambient CO_2 (aCO_2) experimental areas.

2.1 Valve assembly for CO_2 control

A number of pneumatic valves and associated fittings (SMC Pneumatics, Australia, Pty Ltd, VIC) are assembled in a particular order and then connected to AGFACE ring in the field to control CO_2 gas supply (Fig.2). The function of each component is described below.

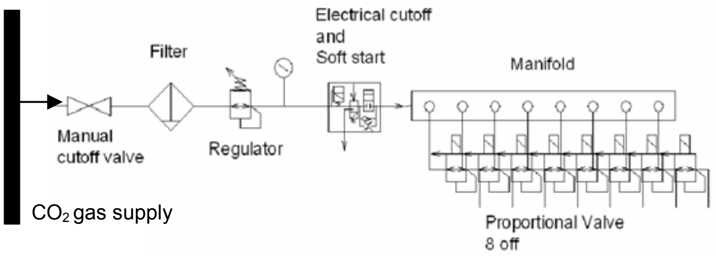

Fig.2. The order of connecting pneumatic valves for CO_2 control at each ring (adapted from Huzzey and Pyke 2007).

Manual cut-off valve: The manual cut-off valve (Fig.2) allows the CO_2 gas supply to each ring to be turned off independently for maintenance.

Filter: A filter is next in the flow line (Fig.2) to trap moisture or small particles, so subsequent components do not malfunction.

Regulator: The regulator (Fig.2) helps to stabilise the subsequent manifold pressure irrespective of the supply line pressure and enables a different pressure to be used at the manifold than the supply line, if required.

Electrically *controlled cut-off / soft-start valve:* From the regulator, the gas flows through an electrically controlled cut-off valve / soft start valve (Fig.2). This valve enables the gas flow to be turned on and off by the microcontroller.

Manifold: The gas flows from the 'soft start' to an eight port manifold (Fig.2). Eight proportional valves, one for each side of the octagon ("ring") (Fig.1), are connected to the manifold.

Proportional valves: The proportional valves (Fig.2) control the rate of flow of gas to the fumigation tubes. These valves can be controlled either using a voltage or current input signal. AGFACE proportional valves use a 4 to 20 mA current signal, because unlike voltage-control, current-control allows the valves to be located a significant distance from the control system, which can be very useful in the design of the FACE array. The voltage drop that occurs over a length of cable can cause unreliable operations.

2.2 CO_2 delivery lines and fittings

Sufficiently flexible low density polyethylene tubes (Brotec Services, VIC, Australia) with 12 mm OD and 800 kPa pressure rating has been used to deliver CO_2 gas to each fumigation tube (a sector of an octagonal ring) through a proportional valve. Push-in fittings (SMC Pneumatics (Australia) Pty Ltd, VIC) have been used throughout to connect the delivery tubes to the valves and the stainless steel fumigation lines. The gas is emitted through 0.3 mm laser drilled holes spaced 50 mm apart. The precise laser drilling of the orifices means flow rates are very similar between each hole.

2.3 CO_2 sampler and analyzer

AGFACE uses ten Infra Red Gas Analysers (IRGA) manufactured by PP Systems (McVan Instruments Pty Ltd, VIC, Australia) to determine CO_2 levels in each eCO_2 rings and in two ambient (aCO_2) rings. AGFACE uses the base SBA-4 model which is an Original Equipment Manufacturer (OEM) board that comes as a complete package, enabling a significant cost saving. All IRGAs used are single frequency design and use an absorber column to obtain a zero reference.

The SBA-4 OEM board required the addition of an absorber column, an air pump capable of 0.15 to 1 L/min flow, an adjustable flow indicator, a calibration potentiometer and a filter. All these components are housed in a waterproof and dustproof enclosure (Rittal Pty Ltd, VIC, Australia). The analysers used to measure the aCO_2 in the two control rings are of the same design except that a wireless modem is housed in the same enclosure to send data directly back to the computer in the site office.

2.4 Wind sensors

The Gill MicroVane and 3-Cup anemometer (Campbell Scientific Australia, QLD) are used in AGFACE for measuring wind direction and speed at a height of 2.0 m above the ground. This sensor is more accurate at low wind speeds and available with a frequency wind speed output which is expected to be more reliable and require less maintenance than other models.

2.5 Power supply

All components in the control system of AGFACE use 12 V DC and or 24 V DC supply. Employing the two different DC voltages gives more flexibility and reliability reducing the risk of interference between components.

2.6 Control system and control algorithm

The 'Z-World' (now Rabbit Semiconductor) SR9000 system as used at SoyFACE (University of Illinois 2007) was chosen for the AGFACE controller. The control algorithm is written in 'Dynamic C', providing the programming flexibility of 'C' and is of industrial quality, design and manufacture (Huzzey and Pyke 2007). Also, the modular design of the algorithm allows for flexibility in the inputs and outputs used. This type of controller is widely used in direct CO_2-injection FACE systems because of its cost-effectiveness. It has a low power requirement.

The core proportional integral derivative (PID) control section of the algorithm was developed by Miglietta *et al*. in Italy (Huzzey and Pyke 2007). The controller software used at SoyFACE was made available to AGFACE and permission was given to modify the algorithm to suit AGFACE requirements.

The control system is programmed to sense the CO_2 concentration, wind speed and direction at the centre of the ring. This is to determine the location of upwind sectors from which the necessary volume of CO_2 need to be released to maintain the target concentrations (550 ppm) at ring-centres. The control system is also programmed to turn the CO_2 off if the average wind speed reaches or exceeds 10 m/s (maximum limit) for 45 seconds and release relatively smaller volumes from all sectors when wind speeds are below 0.3 m/s for 45 seconds.

Carbon dioxide is vented only during the daylight hours (photoperiod) from emergence until maturity of the annual crops studied.

2.7 Data monitoring and data acquisition

A wireless Ethernet local area network (LAN) is installed to monitor and collect data from the individual AGFACE rings. A wireless modem is located within each controller enclosure and each controller has its own Internet Protocol (IP) address. The Elpro 905U-E Ethernet wireless modem (EDAC Electronics, VIC, Australia) was selected for data monitoring and data acquisition for AGFACE as the same unit can be setup to either receive data in the site office or send data from a controller or from the aCO_2 analyser.

The CO_2 concentration, wind speed and wind direction, voltage to proportional valves (Vvalue), and the identification number of the main sector (one of the eight fumigation tubes) releasing CO2 are recorded by the controller every second and these data are averaged over a minute. Then wireless modems transmit one second data every fourth second and one minute data every minute to a computer in the site office. Every fourth second's data are logged to a daily second data files (eg "Ring 9_SecData_011007.csv") for each ring. One minute average data are also logged to a daily file and appended to a cumulative one minute data file for each ring. The time recorded in the cumulative minute data file is the time at the end of the relevant minute.

If a ring stops releasing CO_2 the Vvalues are recorded as zeros. These values are >0 when a ring is releasing CO_2, however the controllers override these values to zeros to turn the CO_2 off if the average wind speed stays ≥10 m/s (maximum limit) for 45 seconds.

A Visual Basic monitoring and data logging program was obtained from SoyFACE and then modified extensively to suit the local AGFACE array (Huzzey and Pyke 2007). This program currently displays one second data, updated every four seconds. The data includes CO_2 concentration (ppm) at the centre of the ring, voltage values for the proportional valves, wind speed (m/s) and direction (degrees). Current-input signals are used to operate these valves but proportional-voltage values are displayed avoiding further modification of logging program. The program has the ability to plot the CO_2 concentration data at the centre of any ring.

A wireless NextG Modem (Telstra, Australia) and LogMeIn software (LogMeIn Inc., USA) are being used for remote access and downloading of data.

2.8 Temporal variation of CO_2

The sensed CO_2 concentration from each ring is recorded every second and averaged over a minute. The data for every fourth second and minute-averages are logged to a computer in the site office. These data are available to evaluate the effect of wind speed on the stability of CO_2 concentration in the middle of the ring.

2.9 Spatial variation of CO_2

A compact, lightweight, field portable CO_2 analyser (EGM-4 Environmental Gas Monitoring for CO_2, McVan Instruments Pty Ltd, VIC, Australia) was used to measure the variability of CO_2 concentrations in a horizontal plane inside and neighbouring outside of each AGFACE ring on four occasions (18 and 19 September 2007, and 24 and 25 October 2007) during the growing seasons. During this period four readings were taken at each of 36 sampling locations at the height of the CO_2 sampler (top of crop canopy) at the centre of each ring.

3. RESULTS AND DISCUSSION

3.1 Temporal variation

Fig.3 shows a trace of the wind speed and 1 minute averaged CO_2 concentrations for one ring on one day. On this day, the wind speed ranged from less than 1 m/s to more than 5 m/s, however the CO_2 concentrations was maintained near 550 ppm irrespective of wind speed (Fig.4).

When taken over a longer period, on average the control system maintained the concentration of CO_2 at the centre of the ring at ≥90% of the target (ie. ≥495 ppm) for 97% of the time (Table1). While operational (during the daylight hours), the typical mean CO_2 concentration inside the ring was 550 ppm with the standard deviation of 28 ppm.

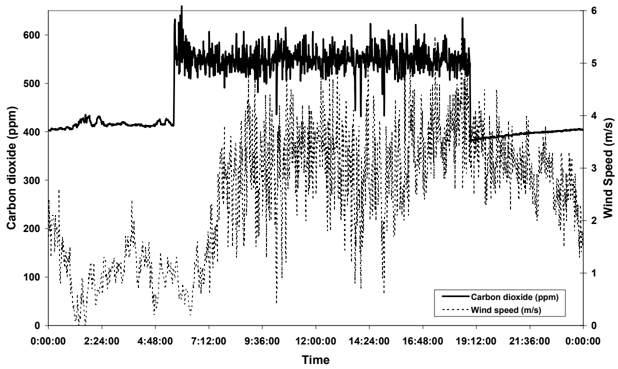

Fig.3. CO_2 and wind speed data logged on 24 October 2007 from an AGFACE ring.

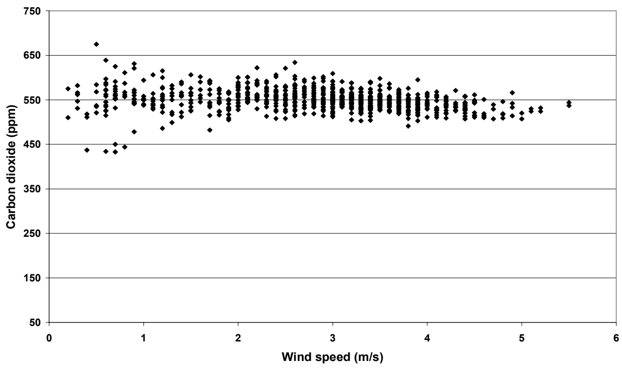

Fig.4 CO2 concentration at the centre of an AGFACE ring graphed against wind speed from data logged on 24 October 2007 (Fig.3).

Table1. Average performance of 8 AGFACE rings in terms of controlling CO_2 concentration at the centre of the ring (the range is given in square brackets).

Total CO_2 injection (hr)	Average CO_2 concentration inside the ring while operational (during daylight only)				% of time CO_2 ≥ 90% of the target.
	Target (ppm)	Median (ppm)	2.5 centile (ppm)	97.5 centile (ppm)	
786	550	548 [547-550]	484 [405-505]	625 [609-701]	97 [92-98]

3.2 Spatial variation of CO_2

The data collected within the AGFACE rings using the portable CO_2 analyser showed that in general, the rings complied with the protocol requirement, that at least 80% of the ring area received ≥90% of the target CO_2 concentration. For example, on 24 October 2007, 98% of the area inside a ring received ≥90% of the target CO_2 concentration (*ie*. ≥495 ppm) (Fig.5).

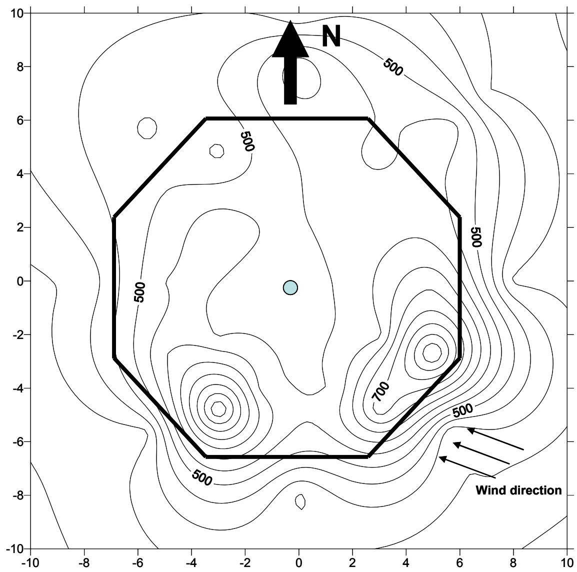

Fig.5. An example of CO_2 distribution in and around a ring on 24 October 2007.

Fig.5 was derived using data collected when the wind was predominantly blowing from the south-east. Consequently, three upwind sectors from south-eastern corner released CO_2 upwind at concentrations >550 ppm, and then the prevailing wind blew CO_2 over the ring. As expected the concentration was gradually diluted as CO_2 travelled to the opposite end of the ring. It is important that the crop grown inside an AGFACE ring should receive uniform concentrations of CO_2 during a growing season to maximise the area for core agronomical experiments.

Wind direction, and hence the locations of CO_2 releasing sectors change very rapidly as well as vary between days and seasons. These variations result in an even distribution of CO_2 inside the ring in the long-term providing the direction of the wind is reasonably even.

Long-term and frequent data collection is planned for 2008 to understand the system performance in detail and fine tune the control system, if needed.

4. CONCLUSION

Careful choice of locally available industry standard components and use of local expertise have enabled significant cost savings in AGFACE construction. Operations in 2007 have shown that the control system for AGFACE facility in Horsham, Victoria, Australia has met the general design standards for FACE experimentation. More data will be collected in 2008 to better understand system performance and fine tune the system.

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REFERENCES

Hendrey GR, KF Lewin, J Nagy (1993). Free-air carbon dioxide enrichment: Development, progress and results. Vegetatio, 104, 17-32.

Hovenden MJ, Miglietta F, Zaldei A, Vander Schoor JK, Wills KE, Newton PCD (2006). The TasFACE climate-change impacts experiment: design and performance of combined elevated CO2 and temperature enhancement in a native Tasmanian grassland. Australian Journal of Botany, 54, 1-10.

Huzzey EH, Pyke WJ (2007) National grains-FACE project. Part2, design specifications for FACE arrays. Internal report to University of Melbourne and Department of Primary Industries, Victoria. Land Technology, Laharum, Victoria, Australia.

Lewin KF, GR Hendrey, J Nagy, RL LaMorte (1994) Design and application of a free-air carbon dioxide enrichment facility, Agricultural and Forest Meteorology, 70, 15-29.

Miglietta F, Peressotti A, Primo Vacari F, Zaldei A, De Angelis P, Scarscia Mugnozza G (2001) Free-air CO2 enrichment of a poplar plantation: the POPFACE fumigation system. New Phytologist, 150, 465-476.

Okada M, Lieffering M, Nakamura H, Yoshimoto M, Kim HY, Kobayashi K (2001) Free-air enrichment (FACE) using pure CO2 injection: system description. New Phytologist, 150, 251-260.

University of Illinois (2007). SoyFACE. http://www.soyface.uiuc.edu/index.htm. Accessed on 1.11.07.