Know the factors that affect the usage of CO_2 in a FACE system and adjust accordingly

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Abstract: A range of technologies/approaches have been used to assess the effect of elevated carbon dioxide (CO_2) concentration on agricultural experimentations. Free-Air CO_2 Enrichment (FACE) systems typically produce an environment more akin to field conditions than other available technologies. FACE is a field-based technique used by scientists to investigate how crop, forest and natural plant communities will respond to future levels of increased atmospheric CO_2 concentration. The major operational cost of running a FACE system is the CO_2 gas. However, the relative importance of the factors that affect usage of CO_2 gas in FACE systems has not been well documented. To rectify this, data collected from the Australian Grains FACE (AGFACE) experiments during September – November 2010 were analysed to determine the effects of wind speed, relative humidity, air temperature, ring height and gap between fumigation tubes and top of crop canopy (gap) on kg of CO_2 gas used per hour. Regression models showed that wind speed explained 74% of CO_2 gas usage, followed by relative humidity (RH), temperature and ring height. The effects of ring height and gap were negligible. Overall the model accounted for 92.3% of the variation. The unaccounted gas usage was due to unaccounted factors and unexplained errors. Gas usage increased with increasing temperature and decreasing RH under each of six wind speed categories. The correlation between gas usage and temperature or RH was high (r^2 = 0.86 – 0.90) for low wind (0 – 0.9 m/s) but declined gradually with increasing wind speed categories. The regression models will help the FACE community set and adjust the parameters of their FACE systems to run them more cost-effectively.

Key Words
AGFACE, FACE rings, CO_2, CO_2 usage, Australia

Introduction

Free Air CO_2 Enrichment (FACE) technology provides a means by which the atmosphere around growing plants may be modified to realistically simulate future concentrations of atmospheric carbon dioxide (CO_2). FACE systems usually inject pure CO_2 from a series of horizontal pipes arranged as an octal ('ring') within which plants are grown. Experiments using FACE are required because most studies looking at the effect of elevated CO_2 concentrations have been conducted in glasshouses or growth chambers, where there are often artefacts, such as increased temperature, reduced wind and rainfall interception that affect plant growth. In addition, there is, in theory, no limit to plant size, or growth problems caused by the constraint of enclosures in FACE systems, e.g. FACE experiments in forests. Historically and currently, there have been 38 FACE sites in Australia, China, Denmark, Finland, France, Germany, Hungary, India, Italy, Ireland, Japan, Netherlands, New Zealand, Sweden, Switzerland, UK and USA (FACE Database Management System 2012) in a range of environments and plant types. The single most expensive operating cost of these FACE systems is the use of CO_2 gas. Researchers realised that CO_2 gas usage in FACE systems was strongly related to wind speed (Hendrey *et al*. 1999). However, the relative importance of a range of factors that potentially affect usage of CO_2 gas in FACE systems is little understood.

We hypothesised that the likely factors affecting CO_2 usage in a FACE system are wind speed, relative humidity, air temperature, height of the FACE rings and gap between the horizontal fumigation tubes and top of the crop canopy. During September – November 2010 data were collected from a 16-m AGFACE ring at Horsham (36°45′07″S latitude, 142°06′52″E longitude, 127 m elevation) on all the likely factors listed above. The data on the use of CO_2 (kg/h) were also recorded for the same period.

This paper establishes the relative importance of the factors that affect usage of CO_2 gas in AGFACE systems and provides models which should help the FACE community to set and adjust the parameters of their FACE systems to allow them to run more cost-effectively.

Methods

In 2010, the readings collected automatically from an online flow meter (ABB TRIO – WIRL ST 40) in kg/h were averaged over 1 min intervals. Wind speeds recorded by the controllers of eight AGFACE rings were averaged over 1 min into a single figure to log along with the CO_2 usage. The temperature (Temp) and relative humidity (RH) measured in a representative ring from the AGFACE site (Mollah *et al.* 2009) using a multiport CO_2 analyser (Mollah and Fitzgerald 2010; Mollah *et al.* 2011) were used in the analysis. During the growing season the 'ring height' (height of the fumigation tubes above the soil surface) was increased several times to keep the fumigation (injection of CO_2) tubes above the canopy. This created different ring volumes to be filled with CO_2; therefore ring height was used as a factor in the analysis. The gap between the fumigation tubes and the top of the canopy ('gap') changed as the crop grew between each height adjustment of the ring. Canopy heights were measured every fortnight and the canopy growth for each day was interpolated and the gap between fumigation tube and canopy top calculated. Early in the season crop growth is slow, 'ring height' is static, and crop cover is not uniform. Therefore, data collected during spring 2010 (September – November) were analysed to determine the effects of wind speed, relative humidity, air temperature, 'ring height' and 'gap' on kg of CO_2 gas used per hour.

GenStat Version 14 was used to fit a General Linear Model using 1-min average data to assess the relationship between CO_2 usage (5.6 – 1183 kg/h), wind speed (0 – 5.9 m/s), temperature (-0.7 – 23.9 ºC), relative humidity (27 – 94 %), ring height (0.5 – 1.1 m) and gap (-26 – 109 mm).

Results

Wind speeds accounted for about three-quarters of CO_2 gas usage in AGFACE

Analysis showed that 73.8% of the CO_2 gas usage was explained by the wind speed alone and depended on the wind speed category (Table 1). The relative humidity, air temperature and their interaction; and the interaction between wind speed and RH accounted for about 18.5% of the gas consumption. Therefore, overall, the model accounted for 92.3% of the variation. The unaccounted gas usage was due to unaccounted factors and unexplained errors.

The 'ring height' had a statistically significant effect (P = 0.049) but accounted for only 0.27% of the gas usage. The 'gap' had no significant effect (P = 0.073) and accounted for only 0.23% of the gas usage. Due to their negligible contribution, the terms 'gap' and 'ring height' and interaction of the wind and air temperature were omitted from the model. The final model was fitted to assess the relationship between CO_2 usage; wind speed, air temperature and relative humidity (equation 1).

$$CO_2\ usage\ (kg/h) = \beta_1 + \beta_2{*}RH(\%) + 21.74{*}Temp(^{\circ}C) - 0.2082{*}(RH(\%){*}\ Temp(^{\circ}C)) \qquad \textbf{equation 1.}$$

The values of β_1 and β_2 for all wind speed categories are provided to work out the CO_2 usage for each wind speed category (Table 1).

Table 1. The values of β_1 and β_2 (equation 1) for all wind speed categories.

	Wind speed category (m/s)					
	0.0 - 0.9	**1.0 – 1.9**	**2.0 – 2.9**	**3.0 – 3.9**	**4.0 – 4.9**	**5 – 5.9**
β_1	712	683	603	499	531	577
β_2	-6.7	-4.9	-1.7	2.08	2.71	2.99

For users' convenience, the CO_2 usage at various temperature and RH were calculated (Table 2 and Table 3) from the model (equation 1). The model, Table 2 and Table 3 will help engineers and scientists to estimate CO_2 usage for a given wind speed category, temperature and relative humidity for their FACE systems. The model can assist in designing a cost-effective FACE system and set the parameters appropriately, e.g. top operational wind speed.

CO_2 usage in AGFACE increased with increasing temperature and wind speed

Figure 1 and Table 2 show the impact of temperature on CO_2 usage in AGFACE. The usage of CO_2 gas in FACE systems is proportional to wind speed, corroborating with a previous study (Hendrey *el al.*1999). Gas usage reaches its peak when high winds combine with high temperatures (Fig.1). However, the correlation between gas usage and temperature was high (r^2 = 0.86) for low wind (0 – 0.9 m/s) but declined gradually with increasing wind speed categories (e.g. r^2 = 0.42 for wind speed category of 5 – 5.9 m/s) such that as wind speed increased, the effect of temperature decreased. There was no statistically significant interaction between wind speeds and air temperature.

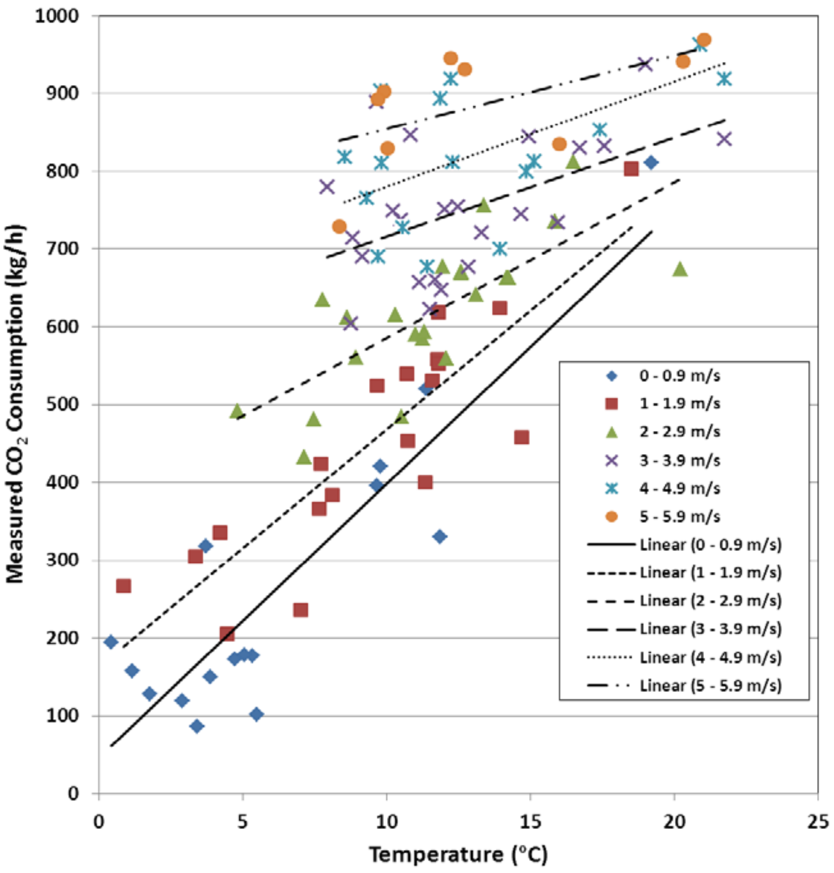

Figure 1. Impact of temperature on CO_2 usage.

Usually, high temperature is followed by high winds and they peak in the afternoon resulting in the highest usage of CO_2 in the afternoon.

Our experiences suggest, reducing the upper limit of the wind speed (e.g. to 5 m/s) and shutting down the system on very hot days (say at > 35°C) will save a significant amount of CO_2. However, these may not be acceptable in some FACE systems, like AGFACE.

Past study (Jifon & Wolfe 2005) suggests that the interaction of elevated CO_2 and high temperature (35ºC) reduces the CO_2 stimulation of photosynthesis and productivity in bean and possibly other heat-sensitive species.

Table 2. Usage of CO_2 (kg/h) at different temperatures and wind speed categories calculated using the model (equation 1) for mean RH (63.58%) during the experiment.

	Wind speed category (m/s)					
	0.0 - 0.9	1.0 – 1.9	2.0 – 2.9	3.0 – 3.9	4.0 – 4.9	5.0 – 5.9
			CO_2 usage			
Temp. (°C)	**(kg/h)**	**(kg/h)**	**(kg/h)**	**(kg/h)**	**(kg/h)**	**(kg/h)**
-5	265	314	424	517	640	680
0	330	379	490	582	705	745
5	396	445	555	648	771	811
10	461	510	621	713	836	876
15	527	576	686	779	902	942
20	592	641	752	844	967	1007
25	657	707	817	910	1033	1073
30	723	772	883	975	1098	1138
35	788	838	948	1041	1164	1204
40	854	903	1013	1106	1229	1269
45	919	969	1079	1172	1295	1335

CO_2 usage in AGFACE decreased with increasing RH

CO_2 gas usage declined with increasing R.H. (Table 3 and Fig. 2) and the correlation was high for low wind (e.g. r^2 = 0.9 for 0 – 0.9 m/s and r^2 = 0.8 for 1 – 1.9 m/s wind categories) but it declined gradually with increasing wind speed categories (e.g. r^2 = 0.2 for wind speed category of 5 – 5.9 m/s). It is expected that the

CO_2 gas usage for a FACE system would be lower in cold and humid areas of Europe compared with hot and dry areas like Australia.

Table 3. The usage of CO_2 at different RH and wind speed category calculated using the model (equation 1) for mean temperature (11.6°C) during the experiment.

	Wind speed category (m/s)					
	0.0 - 0.9	1.0 – 1.9	2.0 – 2.9	3.0 – 3.9	4.0 – 4.9	5.0 – 5.9
			CO_2 usage			
R.H. (%)	(kg/h)	(kg/h)	(kg/h)	(kg/h)	(kg/h)	(kg/h)
0	848	903	885	928	874	852
10	784	838	842	894	871	860
20	719	772	799	860	868	868
30	655	707	757	826	865	876
40	590	641	714	792	863	884
50	526	576	671	758	860	892
60	462	511	628	724	857	901
70	397	445	585	690	854	909
80	333	380	542	655	851	917
90	268	314	500	621	849	925
100	204	249	457	587	846	933

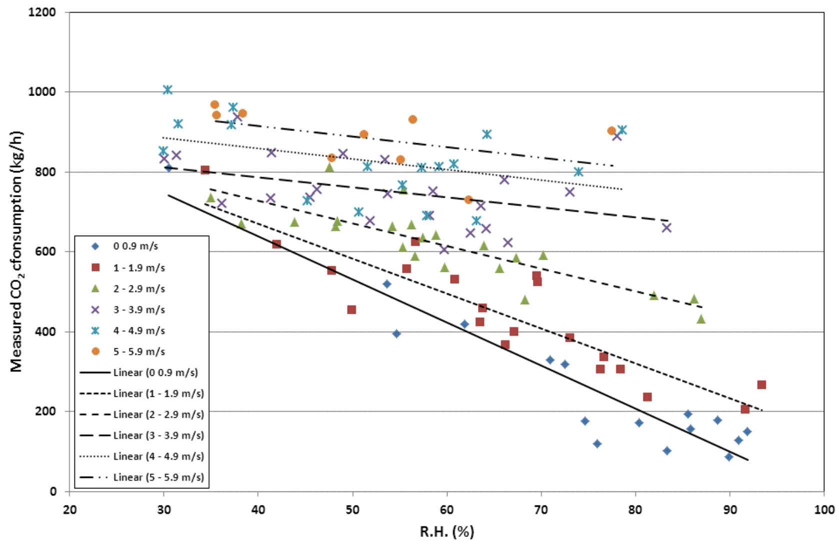

Figure 2. Impact of RH on CO_2 usage

Conclusions

Wind speed is most important single factor in AGFACE system accounting for about three-quarters of CO_2 usage. This effect is expected to apply also to overseas FACE systems.

Around 18.5% of CO_2 usage was explained by the combined effects of temperature, relative humidity and wind speed. FACE systems in hot and dry areas are expected to use relatively more CO_2 than their counterparts in wet and cool areas.

If acceptable as the methodology, it is recommended to reduce the upper limit of the wind speed and shut down the system on hot days to save CO_2.

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