Global Change Biology (2009) **15**, 388–395, doi: 10.1111/j.1365-2486.2008.01748.x

Comparison of gas use efficiency and treatment uniformity in a forest ecosystem exposed to elevated [CO_2] using pure and prediluted free-air CO_2 enrichment technology

KEITH F. LEWIN*, JOHN NAGY*, W. ROBERT NETTLES*, DAVID M. COOLEY* and ALISTAIR ROGERS*†

**Environmental Sciences Department, Brookhaven National Laboratory, Upton, NY 11973-5000, USA, †Department of Crop Sciences, University of Illinois at Urbana Champaign, 1201 West Gregory Drive, Urbana, IL 61801, USA*

Abstract

A direct comparison of treatment uniformity and CO_2 use of pure and prediluted free-air CO_2 enrichment (FACE) systems was conducted in a forest ecosystem. A vertical release pure CO_2 fumigation system was superimposed on an existing prediluted CO_2 fumigation system and operated on alternate days. The FACE system using prediluted CO_2 fumigation technology exhibited less temporal and spatial variability than the pure CO_2 fumigation system. The pure CO_2 fumigation system tended to over-fumigate the upwind portions of the plot and used 25% more CO_2 than the prediluted CO_2 fumigation system. The increased CO_2 use by the pure CO_2 system was exacerbated at low wind speeds. It is not clear if this phenomenon will also be observed in plots with smaller diameters and low-stature vegetation.

Keywords: CO_2, FACE, forest, free-air CO_2 enrichment

Received 5 May 2008 and accepted 22 June 2008

Introduction

In the last 250 years, the atmospheric carbon dioxide concentration ([CO_2]) has risen from 280 to 381 μmol mol^{-1} and within the next 50 years is projected to reach 550 μmol mol^{-1} (Meehl *et al.*, 2007). Understanding the response of plants to rising [CO_2] is a critical component of understanding perturbations in the coupling between changes in the climate system and biogeochemical cycles (Denman *et al.*, 2007) and for providing improved estimates of future global food supply (Parry *et al.*, 2004; Ainsworth *et al.*, 2008 b). Experiments conducted in controlled environments and open-topped chambers have been critical to developing understanding of plant and ecosystem responses to rising [CO_2], but a range of technical limitations necessitated the development of fully open-air field studies where plants could be exposed to elevated [CO_2] in their natural environment using free-air CO_2 enrichment (FACE) technology (Lewin *et al.*, 1992, 1994; Hendrey *et al.*, 1993; McLeod & Long, 1999; Long *et al.*, 2004).

Current FACE systems fumigate plots using either pure CO_2 or CO_2 prediluted with air (Lewin *et al.*, 1992, 1994; Hendrey *et al.*, 1993; Miglietta *et al.*, 1997, 2001; Dickson *et al.*, 2000; Okada *et al.*, 2001; Rogers *et al.*, 2004; Hendrey & Miglietta, 2006). Apart from the approach to CO_2 release, most FACE designs are similar in their layout and operation. A typical FACE plot is approximately circular with a diameter of up to 30 m, and is surrounded by a ring of either vertically or horizontally oriented pipes that release either air enriched with CO_2, or pure CO_2, at vertical intervals from just above the ground to just above the top of the plant canopy. A computer-based control system maintains target [CO_2] levels within each plot by adjusting the quantity of CO_2 released on the upwind side of the plot based on measurements of [CO_2] at the center of the plot, wind direction, and wind speed.

The pure CO_2 FACE system has four main advantages over the prediluted system: (1) the initial construction costs are considerably lower; (2) there are fewer moving parts to maintain; (3) there is less infra-

Correspondence: Keith F. Lewin, tel. + 1 631 344 3458, fax + 1 631 344 2060, e-mail: lewin@bnl.gov

structure, which allows rapid deployment and retrieval when used in annual crop studies; and (4) the pure CO_2 system does not use blowers to predilute the CO_2. At low wind speeds, the turbulence introduced by the blower-driven jets can alter the microclimate inside the plot, resulting in measurable increases in canopy temperature and alteration of frost formation on cool, calm nights (Pinter *et al.*, 2000). At present, most FACE sites do not fumigate at night, and many do not fumigate when ambient temperatures are below 4 °C, thereby greatly reducing the potential impact of the ''blower effect,'' especially in large plots (He *et al.*, 1996).

The first generation of FACE experiments has either been completed or will be closed down in the near future (Ehleringer *et al.*, 2006), and workshops to identify the next generation of experiments are well underway (e.g. FACEing the Future: Planning the Next Generation of Elevated CO_2 Experiments on Crops and Ecosystems, sponsored by the European Science Foundation, Interdisciplinary New Initiatives Fund, Rome, Italy, 5–7 December 2007; Exploring Science Needs for the Next Generation of Climate Change and Elevated CO_2 Experiments in Terrestrial Ecosystems, sponsored by the United States Department of Energy, Arlington, VA, 14–18 April 2008). These next-generation facilities will likely need to be larger, include interactions with other climate change variables, utilize increased replication and provide reduced spatial and temporal [CO_2] variability to maximize the statistical power (Ainsworth *et al.*, 2008a). While there is indirect evidence that prediluted CO_2 fumigation systems perform better than pure CO_2 fumigation systems (Okada *et al.*, 2001), there has never been a direct comparison of the performance of the two fumigation systems under identical conditions. Although initial infrastructure costs will be a significant consideration in future FACE facility designs, purchasing CO_2 is one of the largest expenses in operating a FACE facility (Hendrey & Miglietta, 2006).

The quantity of CO_2 used in a FACE experiment is primarily a function of volume fumigated, wind speed, and atmospheric stability (Nagy *et al.*, 1992), so pure and prediluted fumigation techniques should have similar CO_2 use. On average, the additional moles of CO_2 required to increase the mixing ratio in a unit volume of air at the central sampling point is a matter of mass balance and should not depend *per se* on whether the gas added at the upwind edge of the plot was diluted or not. However, the efficiency and variability of delivery from the edge to any point may depend on the details of injection technique. Empirical evaluation of CO_2 use and the spatial and temporal uniformity of CO_2 enrichment will inform decisions about the design of future large-scale CO_2 enrichment experiments.

We built a vertical release pure CO_2 fumigation system and superimposed it on an existing prediluted CO_2 FACE experiment located in a forest ecosystem. The two systems were operated on alternate days to address two questions: (1) do the pure and prediluted CO_2 fumigation systems provide similar spatial and temporal CO_2 uniformity, and (2) is CO_2 use comparable between the two systems.

Materials and methods

The experiment was conducted at the Forest-Atmosphere Carbon Transfer and Storage (FACTS-1) FACE Research Facility, located in the Blackwood Division of the Duke University Research Forest, in Chapel Hill, NC, USA (35°59′N, 79°6′W, 163 m elevation). The site characteristics and experimental design have been described previously (Hendrey *et al.*, 1999). At the time of this study (August–November 2007), the FACTS-1 Facility included four FACE plots (numbered 2, 3, 4, and 7), where the atmospheric CO_2 concentration was elevated to 200 μmol mol^{-1} above ambient during daylight hours, and four control plots (numbered 1, 5, 6, and 8) that experienced only ambient CO_2 concentrations. Plots were sited within the 19 ha facility based on soil and vegetation characteristics. Each plot was separated from its nearest neighbors by at least 100 m to minimize cross-plot contamination. The study described in this report was conducted in Plot 4, one of the CO_2-enriched FACE plots. The forest canopy at the FACTS-1 Facility consisted primarily of loblolly pine (*Pinus taeda* L.), with individuals of various other dominant and understory species. The tallest trees in Plot 4 measured 23 m, and canopy closure was attained at approximately 21 m.

The prediluted CO_2 fumigation system delivered prediluted CO_2 through large piping to emitter ports located along 32 vent pipes suspended vertically from above the canopy down to the soil surface. The number and spacing of the emitter ports on each vent pipe were adjusted empirically, based on data from a 31-point multiport sampling system, to provide a uniform vertical and spatial [CO_2] distribution. Pure CO_2 injection FACE designs usually use perforated horizontal tubing placed at or just above the top of the plant canopy (Miglietta *et al.*, 1998). Suspending horizontal lines within a tall, dense forest canopy is problematic, because limb and trunk movement during windy conditions will cause damage to the limbs and tubing. To overcome this limitation, we designed a pure CO_2 enrichment system using vertical CO_2 distribution tubes with emitter ports located along the length of the tubes. The vertical arrangement allowed the tubes to move with the canopy and contact fewer limbs than would be the case with horizontal tubes. The physical layout of the pure CO_2 fumigation system was similar to the prediluted design, with 32 tubes suspended vertically from above the canopy down to the soil surface and the emitter holes pointing toward the center of the plot. The tubes were suspended off the same towers and cross-arm supports as the prediluted fumigation system vent pipes. They were connected at ground level to a common plenum with individually controlled quarter turn butterfly valves with pneumatic actuators placed between the plenum pipe and the emitter tube. As with the prediluted CO_2 design, valves connected to the eight tubes on the upwind side of the plot were opened when the wind speed measured just above the canopy was $0.4\,m\,s^{-1}$ or greater. This release arc is narrower than commonly used in FACE experiments, but has proven to provide acceptable CO_2 uniformity across the central 25 m diameter area of the plots in this tall canopy experiment while providing a 10% reduction in CO_2 use compared with using a wider arc (data not shown). When the wind speed was less than $0.4\,m\,s^{-1}$, CO_2 was released out of 16 emitter tubes equally spaced around the plot.

The distribution and emitter pipes of the pure CO_2 injection system were constructed from high-density polyethylene tubing. They were sized to allow maximum flow with acceptable pressure drops, and to maintain sufficient pressure under minimal CO_2 demand to ensure adequate flow out of the most distant emitter ports. The main distribution lines had a 52.5 mm internal diameter (ID). The vertical distribution pipes had a 20.9 mm ID, and the emitter holes measured 3.2 mm in diameter. Each emitter tube had 14 ports, with 12 equally spaced ports located between 17 and 19.75 m above grade. The other two ports were positioned at 4.75 and 11 m above grade based on [CO_2] measurements taken throughout the canopy volume using the 31-port air sampling system described in more detail below. The CO_2 supply pressure was between 200 and 250 kPa, depending on the pressure of the refrigerated CO_2 storage container and gas distribution system. CO_2 flow was regulated with the same valve used for the prediluted enrichment system (Model 735-25000-2000, Kurz Instruments Inc., Monterey, CA, USA). The pressure at the base of the vertical pipes ranged between 3.4 kPa at a CO_2 demand of $200\,kg\,h^{-1}$ and 65 kPa at a flow rate of $1200\,kg\,h^{-1}$.

In this study, the same control program and electronics were used for both prediluted and pure CO_2 enrichment. The CO_2 stream was diverted between injection into the outlet of the predilution blower and introduction into the pure CO_2 distribution piping by paired valves controlled by a mechanical timer. This timer switched between pure and prediluted CO_2 fumigation systems every 24 h at midnight. The blower motor control and alarm circuits were also routed through the timer, so that the blower would not operate when the pure CO_2 fumigation system was operating.

The flow rate of the CO_2 injected into the plot was monitored with a mass flow transmitter (Model 452, Kurz Instruments Inc.) inserted into and calibrated for CO_2 flow through a straight section of 77.93 mm ID steel pipe. Flow readings from this sensor were read once each second and recorded once each minute. The FACE control program read the CO_2 concentration near the top of the canopy at the center of the plot every second with a CO_2 gas analyzer (Model LI-6252, LI-COR Biosciences, Lincoln, NE, USA), and recorded the integrated average concentration each minute. These 1-min integrated average CO_2 concentration values were used to compare temporal variability between the two enrichment designs. One-second CO_2 concentration readings and wind speed signals were used in the modified Proportional-Integral-Derivative (PID) control algorithm within the control program to control the CO_2 injection rate. It has been our experience that this software program and control algorithm works well with field plots of various sizes and canopies of markedly different heights and densities, as well as with different enrichment gasses.

The CO_2 concentration at 31 locations within the plot volume was measured using a multiport sampling system that sequentially sampled each location on a 1-min time step, recording the average of the last 30, 1-s readings from a LI-COR LI-6262 CO_2 gas analyzer. Sampling ports were located at the plot center at heights of 1, 4, 7, 10, 14, 17.5, and 19.5 m. Additional sampling ports were located in a North–South, East–West cross pattern at approximately 8 and 12 m away from the plot center, at heights of 1, 10, and 15 m above the forest floor. This sampler also recorded the operational status of the FACE control system and the wind speed, wind direction, [CO_2] target, and [CO_2] at the control point in the FACE plot at the time each averaged sample concentration was recorded.

After the equipment was installed and tested, the system was operated for several weeks to measure and optimize vertical [CO_2] uniformity in the plot for both the prediluted and pure CO_2 treatment systems. Following this optimization, each treatment system was operated for 23 days, with the pure CO_2 delivery system operating on even days of the year (DOY), and the prediluted system on odd DOY.

A variance ratio test (Zar, 1999) was used to examine the difference between temporal [CO_2] uniformity on odd and even days ($n = 14\,512$–$14\,760$ 1-min integrals of [CO_2] collected over 23 days). These data had an asymmetric, leptokurtic distribution and were log-transformed, $x' = \log(x + 1)$, before analysis. The effect of fumigation technology on CO_2 use was tested using a two-tailed *t*-test to examine the difference between CO_2 use on odd and even days (SYSTAT, SPSS Inc., Evanston, IL, USA). The daily CO_2 use in Plots 2, 3, and 7 was averaged to provide a control for differences in CO_2 use between odd and even days that were not attributable to fumigation technology ($n = 23$ days, $\alpha = 0.05$).

Results and discussion

In a 30 m diameter forest FACE plot, the prediluted and pure CO_2 fumigation systems were both able to meet their target [CO_2], but the prediluted CO_2 fumigation system provided better temporal and spatial uniformity and used less CO_2. We attribute this difference to the more powerful jets of the prediluted system that improved CO_2 transport into the plot.

Both CO_2 fumigation technologies were able to maintain average [CO_2] near the enrichment target of $200\,\mu mol\,mol^{-1}$ above ambient and were not significantly different from each other (Table 1). Because of topographical differences and variability in canopy structure, there is considerably different temporal variation in [CO_2] among individual plots (Table 1). In plots that were continuously operated with prediluted CO_2 fumigation, the treatment uniformity showed a small (7% or less) but significantly higher variation on even days (Plot 2: $F_{(2),14760,14591} = 1.19$, $P < 0.001$; Plot 3: $F_{(2),14651,14519} = 1.12$, $P < 0.001$; Plot 7: $F_{(2),\ 14694,14512} = 1.19$, $P < 0.001$; Table 1). However, in Plot 4, which was operated with prediluted and pure CO_2 fumigation systems on alternate days, the standard deviation was significantly and markedly greater (24%, $F_{(2)14624,14494} = 1.61$, $P < 0.001$) on days when the plot was fumigated using pure CO_2 fumigation technology.

The multiple port gas sampling systems in Plots 2, 3, and 4 enabled measurement of the rate of decrease in CO_2 concentration within the upper canopy between the upwind and downwind edges of the plots. Plot-to-plot variability resulted in large differences in the downwind [CO_2] slopes among the three plots. Plots 2 and 3 were operated with prediluted CO_2 fumigation technology on all days, and CO_2 gradients from the emitters to the opposite edges of the plots did not differ between odd and even days (Fig. 1a and b). In contrast, Plot 4 had a steeper gradient of [CO_2] on even DOY compared with odd DOY (Fig. 1c). The findings from our comparison between prediluted and pure CO_2 fumigation systems are consistent with the data from the Rice FACE experiment (Okada *et al.*, 2001). In that study, when a pure CO_2 injection system was operating at low wind speeds ($< 0.3\,m\,s^{-1}$), it markedly over-enriched the outer volume of the 12 m diameter octagonal FACE plots. We believe that the operation of a pure CO_2 system in a larger plot, such as the one used in this study, exacerbated the bowl-shaped [CO_2] response surface observed in the Rice FACE experiment.

Wind speed and turbulence typically increase during the photoperiod, resulting in a diurnal trend in CO_2 use that peaks during the middle of the afternoon. This trend, confirmed at this site, was observed in both pure and prediluted CO_2 fumigation systems. CO_2 consumption was uniformly and significantly ($t_{(2),44}$, $P < 0.05$) greater throughout the day when using the pure CO_2 fumigation system (Fig. 2a). An examination of CO_2 use at different wind speeds showed it to be significantly greater when operating with pure CO_2 fumigation at all but the highest wind speeds, with the most marked increase occurring at low wind speeds (Fig. 2b). Photosynthetically active radiation (PAR) sensors provide a measurement roughly proportional to total solar insolation, which is one of the major factors affecting atmospheric turbulence (Nagy *et al.*, 1992). As PAR increases, CO_2 use increases, likely reflecting the increased size, frequency, or velocity of eddies that flush air from the plot volume (Fig. 2c). At all but the highest PAR levels

Table 1 Comparison of temporal [CO_2] uniformity at the control points on odd and even days during the period of experimentation

	Odd days of year (prediluted CO_2 injection in Plot 4)		Even days of year (pure CO_2 injection in Plot 4)		
Plot	Mean [CO_2] enrichment ($\mu mol\,mol^{-1}$)	Standard deviation ($\mu mol\,mol^{-1}$)	Mean [CO_2] enrichment ($\mu mol\,mol^{-1}$)	Standard deviation ($\mu mol\,mol^{-1}$)	Difference in standard deviation (%)
2	203	78.1	202	81.2	4
3	204	110.4	203	113.2	3
4	201	74.5	198	92.3	24
7	203	67.7	201	72.2	7

Data are 1-min integrals of CO_2 enrichment (plot concentration minus ambient concentration) at the control location (plot center, 17–19.5 m above grade).

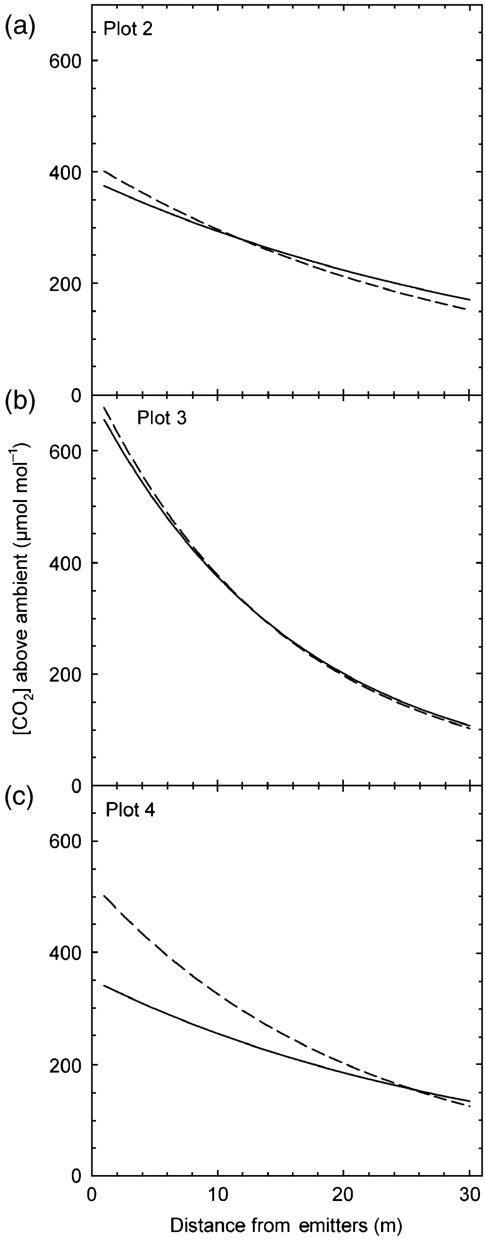

Fig. 1 Rate of decrease in [CO_2] within the upper canopy between the upwind and downwind edges of Plots 2, 3, and 4. CO_2 enrichment of the forest canopy on odd days of year (solid line) and even days of year (broken line) is plotted against distance from the emitters (the ring diameter is 30 m) for Plots 2 [panel (a)] and 3 [panel (b)] which used prediluted CO_2 free-air CO_2 enrichment (FACE) technology on both odd and even days and Plot 4 [panel (c)] which used prediluted CO_2 FACE technology on odd days and pure CO_2 FACE technology on even days. Data were collected from nine sampling points located 15 m above the forest floor. Data were then normalized for wind direction. The [CO_2] at the center of the plot (15 m) is above the target [CO_2] (200 μmol mol^{-1}), because the sampling points for this analysis are positioned closer to the ground than the control sampling point which is located in the upper canopy. Plot 7 did not contain sufficient instrumentation to collect similar information.

CO_2 use was significantly greater in the pure CO_2 fumigation system.

Data from all atmospheric conditions and times of day were combined to estimate the overall CO_2 use (Fig. 3). On odd DOY when all plots were operated with prediluted CO_2 fumigation systems, there was no significant difference in CO_2 use between Plot 4 and the mean of the other plots. However, on even DOY, when Plot 4 was operated with a pure CO_2 fumigation system, Plot 4 used 20% more CO_2 than the average of the other plots. Because of topographical and climatic variation among the plots, a more accurate estimate of CO_2 use in the pure and prediluted CO_2 fumigation systems can be made by comparing CO_2 use in Plot 4 on odd and even days. However, Plots 2, 3, and 7, which were operated using the prediluted CO_2 fumigation technology on all days, averaged 13% [0.26 kg h^{-1} (μmol mol^{-1})$^{-1}$ enrichment] greater CO_2 use on even DOY than on odd DOY. After correcting for this odd–even DOY disparity by subtracting this 0.26 kg h^{-1} (μmol mol^{-1})$^{-1}$ enrichment from Plot 4's daily average CO_2 use on pure CO_2 fumigation days, CO_2 use in Plot 4 was found to be 25% greater [2.43 vs. 1.94 kg h^{-1} (μmol mol^{-1})$^{-1}$ enrichment] when operating with the pure CO_2 fumigation technology ($t_{(2)44}$, $P = 0.014$).

While we believe the emitter tube and port configurations used in this study were adequate for this tall canopy and large plot diameter, there is the potential to improve the performance of either fumigation system through modification of the hardware design or fumigation control program. During the optimization phase of this experiment, we did not see sufficient performance differences to prompt us to use different PID parameters for the pure and prediluted fumigation treatments. However, there is the possibility that additional fine-tuning of these parameters might have improved the temporal performance for one or both fumigation technologies. Optimizing the PID components of the control algorithm requires consideration of many different aspects of the facility design, canopy structure, and meteorological conditions, of which fumigation technology is only one minor component. Control algorithm mistuning would not explain the differences in CO_2 use or downwind concentration gradients observed in this study. The lower emitter port jet strengths present during pure CO_2 injection provide a much simpler and direct explanation for these differences.

The cost of CO_2 is by far the largest single expense at many FACE sites. Unless we can identify free or nearly free sources of CO_2, one of the best ways to reduce the operational costs of the next generation of FACE experiments will be to use designs that provide the most efficient use of CO_2. In this study, we have shown that pure CO_2 fumigation technology used approximately

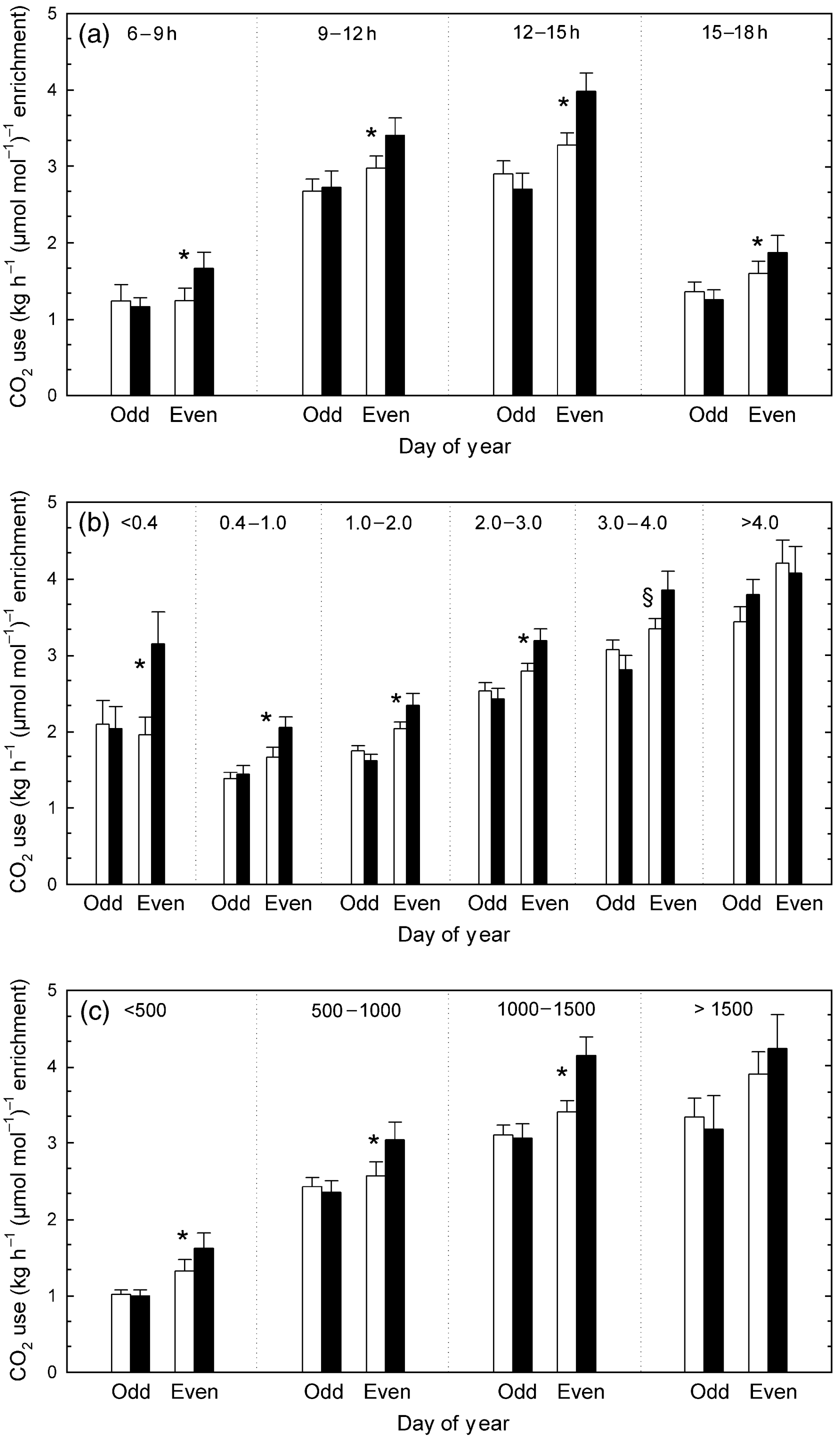

Fig. 2 Variation in CO_2 use between pure and prediluted CO_2 fumigation systems. CO_2 use in the average of Plots 2, 3, and 7 (open bars) and in Plot 4 (filled bars) measured on odd and even days of the year over the duration of the experiment. Plots 2, 3, and 7 were operated with a prediluted CO_2 free-air CO_2 enrichment (FACE) system on all days. Plot 4 was operated with prediluted CO_2 FACE technology on odd days and pure CO_2 FACE technology on even days. Panel (a) shows CO_2 use during the hours of operation (daylight fumigation only). Panel (b) shows CO_2 use for a range of wind speeds (m s^{-1}). Panel (c) shows CO_2 use for a range of photosynthetically active radiation (PAR, μmol m^{-2} s^{-1}). Bars show mean + SE ($n = 23$ days); $^{*}t_{(2),44}$, $P<0.05$, $^{\S}t_{(2),44}$, $P<0.1$.

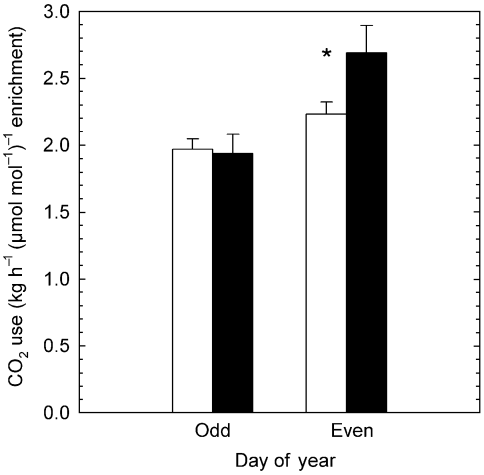

Fig. 3 CO_2 use in the average of Plots 2, 3, and 7 (open bars) and in Plot 4 (filled bars) measured on odd and even days over the duration of the experiment. Plots 2, 3, and 7 used prediluted CO_2 free-air CO_2 enrichment (FACE) technology on all days. Plot 4 alternated between prediluted CO_2 FACE technology (odd days) and pure CO_2 FACE technology (even days). Bars show mean ± SE ($n = 23$ days). Asterisk (*) denotes a significant ($t_{(2),44}$, $P < 0.05$) difference in CO_2 use between Plot 4 and the average of the three other plots.

25% more CO_2 than prediluted CO_2 fumigation technology, equivalent to a USD 200 000 increase in annual CO_2 costs at the FACTS-1 experiment. Based on the difference between the hypothetical 2008 construction costs for the FACTS-1 Facility and the cost of building the same facility using pure CO_2 fumigation technology, we estimate that the CO_2 savings demonstrated in this study would exceed the additional construction costs of the prediluted CO_2 technology within the facility's first year of operation.

It is not known if the results from this study will translate to smaller diameter, lower stature FACE experiments, or whether the potential savings would be large enough to offset the advantages of pure CO_2 fumigation in other experimental designs. Maximizing treatment uniformity and minimizing operational costs are key technological goals for the next generation of FACE experiments (Ainsworth *et al*., 2008a). Additional comparisons of existing and emerging FACE technologies are urgently required to select the best CO_2 fumigation technology for future large-scale experiments.

Acknowledgements

We acknowledge support from the U.S. Department of Energy (DOE), Office of Science, Biological and Environmental Research (BER) program, and by the U.S. Department of Energy Office of Science contract No. DE-AC02-98CH10886 to the Brookhaven National Laboratory.

References

Ainsworth EA, Calfapietra C, Cuelemans R *et al*. (2008a) Next generation of elevated [CO_2] experiments with crops: a critical investment for feeding the future world. *Plant, Cell & Environment*, **31**, 1317–1324.

Ainsworth EA, Rogers A, Leakey ADB (2008b) Targets for crop biotechnology in a future high-CO_2 and high-O_3 world. *Plant Physiology*, **147**, 13–19.

Denman K, Brasseur G, Chidthaisong J *et al*. (2007) Couplings between changes in the climate system and biogeochemistry. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Solomom S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor M, Miller H), pp. 499–587. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Dickson RE, Lewin KF, Isebrands JG *et al*. (2000) *Forest atmosphere carbon transfer storage-II (FACTS II) – the aspen free-air CO_2 and O_3 enrichment (FACE) project in an overview*. General Technical Report, NC-214, USDA Forest Service, North Central Research Station, MN, 68 pp.

Ehleringer J, Birdsey R, Ceulemans R, Melillo J, Nosberger J, Oechel WC, Trumbore S (2006) *Report of the BERAC subcommittee reviewing the FACE and OTC elevated CO_2 projects in DOE*. http://www.sc.doe.gov/ober/berac/FACE_2006_report.pdf

He Y, Yang XS, Miller DR, Hendrey GR, Lewin KF, Nagy J (1996) Effects of face system operation on the micrometeorology of a loblolly pine stand. *Transactions of the ASAE*, **39**, 1551–1556.

Hendrey G, Miglietta F (2006) FACE technology: past, present and future. In: *Managed Ecosystems and CO_2 Case Studies, Processes, and Perspectives* (eds Nosberger J, Long SE, Norby RJ, Stitt M, Hendrey G, Blum H), pp. 15–43. Springer-Verlag, Berlin, Heidelberg, Germany.

Hendrey GR, Ellsworth DS, Lewin KF, Nagy J (1999) A free-air enrichment system for exposing tall forest vegetation to elevated atmospheric CO_2. *Global Change Biology*, **5**, 293–309.

Hendrey GR, Lewin KF, Nagy J (1993) Free air carbon-dioxide enrichment – development, progress, results. *Vegetatio*, **104**, 17–31.

Lewin KF, Hendrey GR, Kolber Z (1992) Brookhaven National Laboratory free-air carbon-dioxide enrichment facility. *Critical Reviews in Plant Sciences*, **11**, 135–141.

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

Long SP, Ainsworth EA, Rogers A, Ort DR (2004) Rising atmospheric carbon dioxide: plants face the future. *Annual Review of Plant Biology*, **55**, 591–628.

McLeod AR, Long SP (1999) Free-air carbon dioxide enrichment (FACE) in global change research: a review. *Advances in Ecological Research*, **28**, 1–56.

Meehl G, Stocker T, Collins W *et al*. (2007) Global climate projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Solomom S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor M, Miller H), pp. 747–845. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Miglietta F, Lanini M, Bindi M, Magliulo V (1997) Free air CO_2 enrichment of potato (*Solanum tuberosum*, L.): design and performance of the CO_2-fumigation system. *Global Change Biology*, **3**, 417–427.

Miglietta F, Magliulo V, Bindi M, Cerio L, Vaccari FP, Loduca V, Peressotti A (1998) Free air CO_2 enrichment of potato (*Solanum tuberosum* L.): development, growth and yield. *Global Change Biology*, **4**, 163–172.

Miglietta F, Peressotti A, Vaccari FP, Zaldei A, deAngelis P, Scarascia-Mugnozza G (2001) Free-air CO_2 enrichment (FACE) of a poplar plantation: the POPFACE fumigation system. *New Phytologist*, **150**, 465–476.

Nagy J, Lewin KF, Hendrey GR, Lipfert FW, Daum ML (1992) Face facility engineering performance in 1989. *Critical Reviews in Plant Sciences*, **11**, 165–185.

Okada M, Lieffering M, Nakamura H, Yoshimoto M, Kim HY, Kobayashi K (2001) Free-air CO_2 enrichment (FACE) using pure CO_2 injection: system description. *New Phytologist*, **150**, 251–260.

Parry ML, Rosenzweig C, Iglesias A, Livermore M, Fischer G (2004) Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change – Human and Policy Dimensions*, **14**, 53–67.

Pinter PJ, Kimball BA, Wall GW *et al*. (2000) Free-air CO_2 enrichment (FACE): blower effects on wheat canopy microclimate and plant development. *Agricultural and Forest Meteorology*, **103**, 319–333.

Rogers A, Allen DJ, Davey PA *et al*. (2004) Leaf photosynthesis and carbohydrate dynamics of soybeans grown throughout their life-cycle under free-air carbon dioxide enrichment. *Plant, Cell & Environment*, **27**, 449–458.

Zar JH (1999) *Biostatistical Analysis*. Prentice Hall, London, pp. 202.