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A free-air enrichment system for exposing tall forest vegetation to elevated atmospheric CO_2

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Abstract

A free-air CO_2 enrichment (FACE) system was designed to permit the experimental exposure of tall vegetation such as stands of forest trees to elevated atmospheric CO_2 concentrations ($[CO_2]_a$) without enclosures that alter tree microenvironment. We describe a prototype FACE system currently in operation in forest plots in a maturing loblolly pine (*Pinus taeda* L.) stand in North Carolina, USA. The system uses feedback control technology to control $[CO_2]$ in a 26 m diameter forest plot that is over 10 m tall, while monitoring the 3D plot volume to characterize the whole-stand CO_2 regime achieved during enrichment. In the second summer season of operation of the FACE system, atmospheric CO_2 enrichment was conducted in the forest during all daylight hours for 96.7% of the scheduled running time from 23 May to 14 October with a preset target $[CO_2]$ of 550 μmol mol^{-1}, $\approx$ 200 μmol mol^{-1} above ambient $[CO_2]$. The system provided spatial and temporal control of $[CO_2]$ similar to that reported for open-top chambers over trees, but without enclosing the vegetation. The daily average daytime $[CO_2]$ within the upper forest canopy at the centre of the FACE plot was 552 $\pm$ 9 μmol mol^{-1} (mean $\pm$ SD). The FACE system maintained 1-minute average $[CO_2]$ to within $\pm$ 110 μmol mol^{-1} of the target $[CO_2]$ for 92% of the operating time. Deviations of $[CO_2]$ outside of this range were short-lived (most lasting $<$ 60 s) and rare, with fewer than 4 excursion events of a minute or longer per day. Acceptable spatial control of $[CO_2]$ by the system was achieved, with over 90% of the entire canopy volume within $\pm$ 10% of the target $[CO_2]$ over the exposure season. CO_2 consumption by the FACE system was much higher than for open-top chambers on an absolute basis, but similar to that of open-top chambers and branch bag chambers on a per unit volume basis. CO_2 consumption by the FACE system was strongly related to windspeed, averaging 50 g CO_2 m^{-3} h^{-1} for the stand for an average windspeed of 1.5 m s^{-1} during summer. The $[CO_2]$ control results show that the free-air approach is a tractable way to study long-term and short-term alterations in trace gases, even within entire tall forest ecosystems. The FACE approach permits the study of a wide range of forest stand and ecosystem processes under manipulated $[CO_2]_a$ that were previously impossible or intractable to study in true forest ecosystems.

Keywords: elevated CO_2, FACE, free-air CO_2 enrichment, forest ecosystem, *Pinus taeda*, trace gas exposure technology

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Introduction

More than one-third of the world's terrestrial landmass is under forest or woodland vegetation or has been until recently. With the atmospheric CO_2 concentration ($[CO_2]_a$) rising it is recognized that experimentation involving forest trees could provide critical information regarding biosphere–atmosphere feedbacks and forest ecosystem carbon storage responses to elevated atmospheric CO_2 concentration (Eamus & Jarvis 1989; Jarvis 1995). Recent data indicate that forests serve as important net sinks for atmospheric CO_2 (Goulden *et al.* 1996) and may store organic carbon for long periods of time due to the slow turnover of pools of carbon stored in wood and soils (Dixon *et al.* 1994; Turner *et al.* 1995). However, experi-

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mentation with trees in true forest plots involves serious logistical difficulties owing to the large size of trees, their stature, their longevity, and other factors. It is now recognized that experiments with seedlings may not necessarily be indicative of the responses of nonjuvenile trees since mature trees differ from seedlings in physiology and morphology and can also differ significantly in their responses to environmental stresses (Lee & Jarvis 1996; Saxe *et al.* 1998). Thus in addition to studies on small, juvenile plants it is important to evaluate the effects of elevated CO_2 on trees in forest stands.

A variety of approaches have been used in fumigation experiments to quantify the effects of increasing $[CO_2]_a$ on plants. Most of these approaches, reviewed elsewhere (Allen *et al.* 1992; Lee & Barton 1993; Saxe *et al.* 1998), entail some type of enclosure or chamber. While chambers provide containment of CO_2-enriched air and in this way reduce the amount of CO_2 required for an experiment, chambers may alter microenvironmental conditions for the plants grown within. For instance, daytime air temperature inside chambers can be more than 3 °C greater than those measured in unconfined plots for considerable periods of time (Drake *et al.* 1989; Wang *et al.* 1995). Moreover, Tissue *et al.* (1996) and Murray *et al.* (1996) have observed significant chamber effects on tree form in enclosed vs. un-enclosed trees. Free-air carbon dioxide enrichment (FACE) is an alternative experimental strategy in which CO_2-enriched air is released into the ambient environment in such a way as to provide effective experimental control over $[CO_2]_a$ without causing appreciable changes in other environmental variables. We describe a prototype FACE system currently in operation in a maturing loblolly pine (*Pinus taeda* L.) stand in North Carolina, USA, and summarize results from the performance of this system in its second growing season of operation.

Other CO_2 enrichment systems employing the FACE approach have been operated by the USDA/ARS Water Conservation Laboratory, Maricopa, Arizona (Hendrey & Kimball 1994; Nagy *et al.* 1994; Kimball *et al.* 1995) and the Institute for Plant Sciences, Swiss Federal Institute of Technology (ETH), Zurich (Hebeisen *et al.* 1997) with Brookhaven National Laboratory. Investigators at the Italian National Research Council also recently developed a smaller-scale crop exposure system (Miglietta *et al.* 1997). While these previous FACE experiments have been conducted in short-stature vegetation $\leqslant$ 2 m height, the challenge of controlling $[CO_2]_a$ throughout a much larger volume as is characteristic of forest plots has been a major impediment to the development of experiments on responses of tall-stature, natural vegetation to elevated atmospheric trace gases. If $[CO_2]_a$ is to be controlled from the ground to the crown of a developing forest, then taller canopies will require that greater amounts of CO_2 be added to maintain the target $[CO_2]$. Also, as tree height increases, it becomes more difficult to control $[CO_2]$ throughout the vertical profile because of the nonuniform character of the wind profile within the canopy. Thus we chose to investigate the tractability of the FACE approach for CO_2 enrichment studies in a rapidly growing loblolly pine forest, a major forest type in the south-eastern USA.

Early types of free-air exposure systems were built in the Netherlands (Mooi & van der Zalm 1985) and England (Greenwood *et al.* 1982; McLeod *et al.* 1985; McLeod 1995) for exposing short-stature vegetation to elevated concentrations of atmospheric trace gases such as O_3 and SO_2. A number of innovations for effective regulation of $[CO_2]_a$ within FACE experiments have been developed for both agricultural and forest FACE experiments, principal among which are the on-line computer regulation of gas concentration using fast feedback control technology without in-line volumetric averaging, and predilution of CO_2 prior to its release into the experimental plot. If tractable in a forest environment, the free-air technique described here and its implementation in a forest ecosystem may lead to more realistic experiments on trees than previous chamber experiments, and provide information to answer priority questions concerning actual forest stands and their potential responses and response mechanisms to changes in trace gas components of the global atmospheric environment.

Materials and methods

Site description

The site in the Blackwood Division, Duke Forest, Orange County, N.C. (35°58′N, 79°5′W) was chosen on the basis of logistical convenience and proximity to researchers, and because loblolly pine vegetation is a major forest type in the south-eastern USA, covering over 20 million ha (Haynes *et al.* 1995). This forest type generally occurs on acidic, nutrient-poor soils but is nevertheless one of the most productive forest types in the U.S. (Fox & Mickler 1996). CO_2 enrichment studies in the loblolly pine forest type are expected to provide insight into possible ecological feedbacks affecting whole-ecosystem carbon storage and other responses to elevated CO_2. Loblolly pine is also one of the most intensively studied species in terms of responses to CO_2 enrichment (Ellsworth *et al.* 1995; Teskey 1995; Tissue *et al.* 1996).

The site is occupied by a loblolly pine forest planted in 1983 following clear-cutting and burning. Currently the forest is dominated by loblolly pine with ≈ 1100 trees ha^{-1}, with major subcanopy tree species such as sweetgum (*Liquidambar styraciflua* L.), winged elm (*Ulmus alata* L.), red maple (*Acer rubrum* L.) and hickory (*Carya* spp.). The loblolly pine overstory trees were ≈ 10 m tall in the summer of 1994 and are increasing in height at a rate approaching 1 m y^{-1}. In August 1995 the stand vegetation area index was 2.9 m^2 m^{-2} ground, with maximum leaf area density at 7–8 m height. The base of the live crown of the dominant and codominant pines was at 6 m above the ground, with hardwood trees contributing to the leaf area index below this height. The site is level at an elevation of 174 m. Further description of the site and a brief description of the FACE system can be found in Ellsworth *et al.* (1995).

Design of the Forest FACE Prototype (FFP)

The overall FACE system design used by Brookhaven National Laboratory was described in Hendrey *et al.* (1993) and Lewin *et al.* (1994), and the forest FACE prototype described here is modified from these earlier designs. The generic FACE system array hardware consists of a high-volume blower, a plenum or wide ring-shaped pipe for air distribution, and 32 vertical standing vent pipes for emitting CO_2 into the exposure volume. These are described in more detail below, including modifications of the FACE design to enable operation in a forest environment.

Two versions of the prototype FACE system in Duke Forest were built in sequence at the same location. These prototypes differed in capacity of the fan, size and configuration of the main distribution plenum, and diameter of the vertical vent pipes (VVPs). The first version of the FFP was assembled in the spring and summer of 1993, and tested during that summer and early fall. Data obtained from this version were used to re-design the system to enhance system performance. The fan, toroidal plenum and VVPs of the first version were replaced with larger components and a second version of the system was built in the spring of 1994. The system was reconfigured in order to increase the predilution of CO_2 prior to release from the VVPs. The new plenum was assembled outside of the circle of VVPs in the second prototype to minimize the impact of the equipment on vegetation within the study area (Fig. 1). This system was operated from 6 June to 31 August 1994, and from 23 May to 14 October 1995. All further description of the system and analysis of performance will refer to the second version of the FFP system which is currently in operation, along with a similarly designed set of replicated FACE rings constructed two years later in the same forest stand with fully instrumented control blower rings. We analyse performance of this version of the FFP in the second season of its operation (1995), although all aspects of this performance were largely similar in the 1994 and 1995 operation periods.

The set-point for atmospheric CO_2 concentration in the FFP in 1994 and 1995 was 550 μmol mol^{-1}, nearly 200 μmol mol^{-1} above ambient $[CO_2]_a$ and similar to the $[CO_2]_a$ anticipated in the middle of the next century (IS-92a emission scenario, Houghton *et al.* 1996). A constant set-point was chosen to simplify analysis of the system performance, although the system can operate in a mode that tracks $[CO_2]_a$ with a constant increment (e.g. + 200 μmol mol^{-1}). In 1994, the FFP system operated 12 h per day. In 1995 the system was operated from civil dawn to civil twilight (when sun elevation angle exceeded – 6° from the horizon) for 133 out of 145 days from 23 May to 14 October. Sporadic tests of continuous 24-h operation were also conducted in 1995. Major subcomponents of the FFP system that will be described in more detail include (i) the CO_2 supply system, (ii) the fan and plenum system, (iii) the vertical vent pipe system, and (iv) the control system.

CO_2 supply system

Carbon dioxide was obtained as a by-product of manufacture of agricultural fertilizer from methane and atmospheric nitrogen. Food-grade, liquefied CO_2 was delivered to the FACE site by truck in 20 000 kg lots and transferred to an insulated receiving tank. Tank pressure was maintained at 1725 kPa to keep the CO_2 in a liquid state. A refrigeration unit and an electric heater maintained this pressure regardless of demand for CO_2 by the FACE control system. Liquid CO_2 was supplied to electrical heat exchangers which vaporize the CO_2 as needed. The gaseous CO_2 was channeled through 5 cm internal diameter metal pipe to a pressure regulator that reduces line pressure to 140 kPa above ambient. The regulator was equipped with a manually actuated shut-off valve and there was also an electrically actuated shut-off valve at the FACE ring. The CO_2 gas was piped from the regulator to the FACE plot at low pressure through 5 cm polyethylene tubing.

CO_2 flow was measured by an electronic flow sensor and throttled by a Kurz rotary ramp metering valve (Model 735, Kurz Instruments, Monterey, CA) that provided a very even, linear gradation of gas flow over the range 0–1550 kg h^{-1}. The metering valve was operated directly by the FACE control computer (described below). CO_2 gas was then injected into the plenum immediately down-stream of the air supply fan.

Fan and plenum

A toroidal plenum was assembled 2 m outside of the 30 m diameter circle of VVPs so as to minimize the impact of the equipment on vegetation within the study area. The plenum was a 34 m diameter torus made of 38 cm diameter polyethylene pipe (Hancor Tite-Line, Hancor Inc., Findlay, OH) connected to the fan at a 'T'

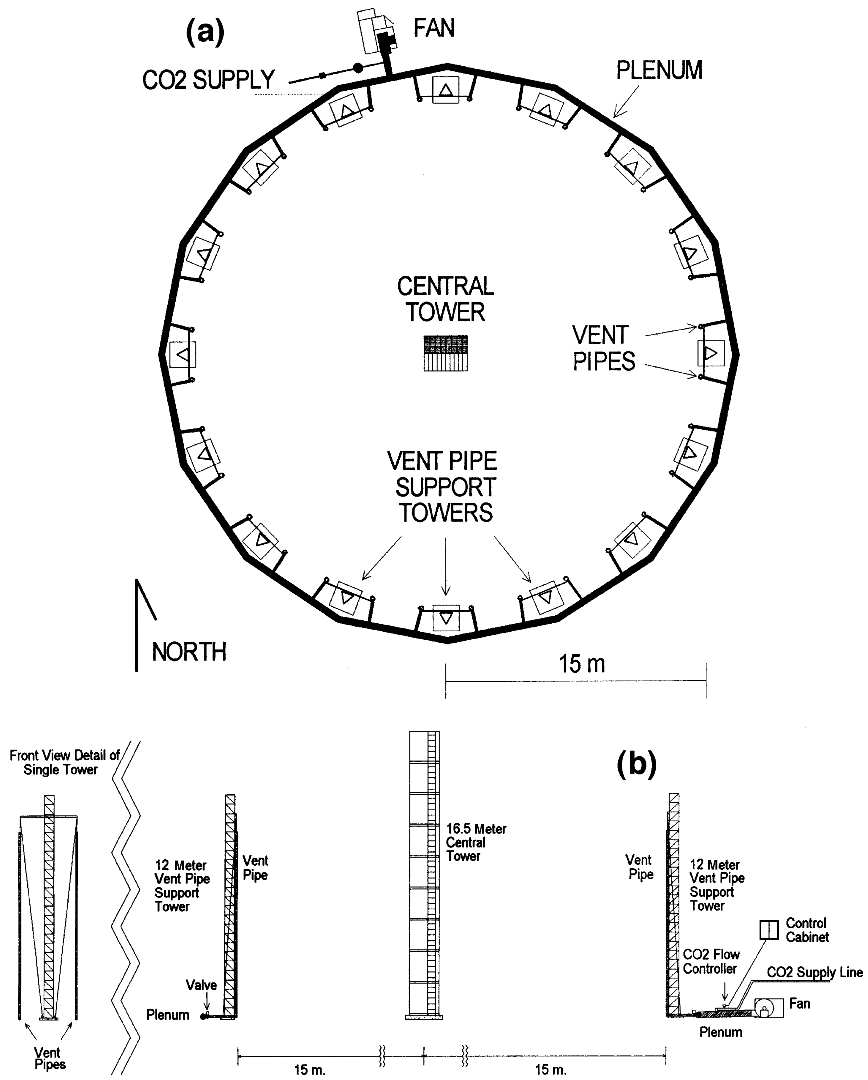


Fig. 1 A schematic layout of the forest FACE prototype in Duke Forest. (a) Overhead view of the layout showing the plenum, location of towers and vertical vent pipes, and fan assembly. The 32 vertical vent pipes are located on either side of the 16 peripheral support towers designated by small triangles in the diagram. (b) A cut-away view through the FACE ring showing positioning of vertical vent pipes suspended from peripheral towers.

by a 2 m length of the same pipe (Fig. 1). A radial fan (Model BCS-165, American Fan Co., Fairfield, OH) was used to provide air flow (102 $m^3 min^{-1}$ at 2.0 kPa pressure) around the plenum. The fan was placed in a 1.5 m tall shed located 5 m north of the VVP circle. The fan intake, with dimensions 1 m × 2 m, was orientated to the west, perpendicular to the radius of the FACE circle.

Vertical vent pipes

Injection of CO_2-enriched air into a face plot takes place at the vertical vent pipes (VVPs). This is the most critical control step in the free-air approach and determines how well [CO_2] is controlled in the FACE plot. The following elements of the system are each adjustable to some degree.

Upwind control. Thirty-two VVPs constructed from 15 cm diameter polyethylene pipe (Hancor smoothwall, Hancor Inc., Findlay, OH) were evenly spaced in a 30 m diameter circle around the FACE plot (Fig. 1). Normally, valves at the bases of the VVPs were opened or closed so as to provide release of CO_2-enriched air from the upwind direction only (Fig. 2). This feature reduced CO_2 losses that would occur if it were released on the downwind side and reduced the potential for carry-over of injected CO_2 to adjacent plots.

Feathered edges. When the wind speed is greater than the stall-speed of the anemometer (0.4 $m\ s^{-1}$) VVPs are opened on the upwind side of the plot. If 16 VVPs of the upwind semicircle are opened, excessive CO_2 concentrations occur near the edges of the plot where tangents are about parallel to wind direction. To prevent this, CO_2 is released from an arc that encompasses 12 VVPs over 135 degrees of the VVP circle. Furthermore, a 'feathering' of the VVPs (Lewin *et al.* 1994) is achieved by keeping the second VVP from each end of the arc of 12 upwind VVPs closed (i.e. only 10 VVPs open). This arrangement was

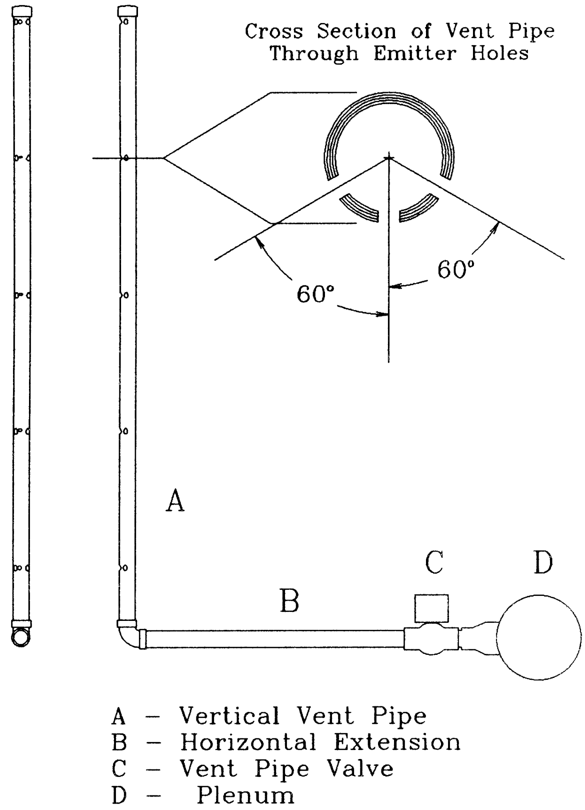


Fig. 2 Detail of the vertical vent pipe assembly (see text for further details).

determined from empirical observations of the arrangement of open VVPs that produced the most even spatial distribution of CO_2 concentration under a wide range of wind speed and turbulence conditions.

Low wind speed regime. Detection of true wind direction becomes unreliable with wind vanes below a minimum stall velocity, which was 0.4 m s^{-1} for the model used (Climatronics Inc., Bohemia, NY). The control-limiting process under these low-wind conditions, is the information feed-forward from the moment of a change in the rate of release of CO_2 to the detection of CO_2 concentrations within the FACE plot. At wind speeds below the anemometer stall threshold, it will take at least 40 s for an adjustment in the rate of CO_2 release to traverse the air handling system, be emitted from the VPPs, and carried across the plot, to be detected at the control point in the centre. Use of a more sensitive anemometer (i.e. sonic anemometer) would not improve control over the concentration of CO_2. Therefore, when wind speed dropped below that threshold for a 20-s period, directional control was terminated and every other VVP around the FACE ring was opened. This is the most problematic condition for maintaining control of CO_2 concentration in a free-air system because (i) transport from the VVP into the plot is very irregular in all three cardinal directions; (ii) low wind speed means that transport of the CO_2-enriched air from the VVP to the sample intake in the centre of the plot for the CO_2 control infrared gas analyser (IRGA) is slowed, increasing feedback delay; and (iii) parcels of air differentially enriched with CO_2 due to lack of mixing may move irregularly through the plant canopy and back into the plot.

Support Towers. To achieve CO_2 exposure of tall trees, two VVPs were suspended from each of 16 12 m tall aluminium towers (Universal Manufacturing Co., Mt. Clemens, MI) that were evenly spaced around the perimeter of the 30 m diameter plot (Fig. 1, Fig. 2). These towers had a triangular profile 76 cm per side at the base, and were set into a base of 4.2 m^3 of concrete. The towers were free-standing and could be climbed. They could be extended in height to 20 m without guying and considerably higher if guyed, and therefore are appropriate for FACE experimentation in a growing forest.

Vertical Vent Pipe valves and emitters. VVPs were connected to 10 cm diameter butterfly valves which were directly connected to the circumferential plenum by a 2 m length of 15 cm diameter polyethylene pipe (Figs 1 and 2). The 10 cm diameter valves were pneumatically actuated and each was separately controlled by the computer control system. These valves opened or closed the VVPs according to wind direction averaged over a 10-s period. Each valve was connected to a manifold of 32 pneumatic valves actuated by the control program (described below) via 12-volt DC solenoids. The pneumatic system was pressurized at 620 kPa with CO_2 from the high pressure side of the CO_2 supply system.

The CO_2-enriched air was emitted at $\approx$ 3% CO_2 (30 000 μmol mol^{-1}) from ports drilled into the VVPs. Ports were arranged in triplets of 2.5 cm diameter holes with one of them directly on a radial line facing the plot centre and the other two set at 60° to each side of centre (Lewin *et al.* 1994). The triplet emitter ports were spaced at 0.5 m vertical intervals from 2 m above the ground to the top of the pipe. Since the wind profile changes greatly with elevation from ground level to several meters above the top of the canopy, the vertical configuration of the emitter ports was adjusted empirically to achieve optimal three-dimensional distribution of [CO_2] within the forest plot by applying plastic tape to cover some of the ports.

CO_2 control system

Regulation of CO_2 concentrations within the FFP and registration and logging of all pertinent data were achieved via a set of three fully integrated subsystems: (i) wind and CO_2 detectors; (ii) data acquisition system; (iii) CO_2 control program; and a separate CO_2 distribution monitoring system.

Wind and CO2 detectors. Wind speed was measured near the top of the canopy by a sensitive cup anemometer (Model 100075, Climatronics, Bohemia, NY) and wind vane (Climatronics model 100076) mounted on one of the VVP towers. The minimum detectable wind speed was 0.3 m s^{-1} and the wind vane was reliable at wind speeds above 0.4 m s^{-1}. For [CO_2] measurements, a nondispersive infrared CO_2 gas analyser, or IRGA (Ultramat 21P, Siemens Corp., Mainz, Germany) located at the centre of the FACE plot continuously monitored [CO_2] at a control point within the canopy. Air was sampled from a control point at the centre of the array, with the inlet height set just above the height of intersecting branches among the trees (9 m in 1995). The sampled air was pumped at 2.5 L min^{-1} through $\approx$ 10 m of 4.3 mm diameter polypropylene tubing before it reached the analyser. The time for the sample to traverse this distance, along with measurement delays inherent in the analyser, resulted in a total delay of 10–12 s between when the air sample entered the sampling tube and when the resulting concentration was delivered to the control program. The CO_2 signal attenuation in the tubing was evaluated by Farrow *et al.* (1992). Tubing used for all CO_2 monitoring was made from opaque, black polypropylene (Impolene, Imperial Eastman, Chicago, IL) with low CO_2 adsorptivity and permeability, and high resistance to ultraviolet radiation.

Accuracy of the Ultramat IRGA is 1% of its full-scale range (0–1000 µmol mol^{-1}), or 10 µmol mol^{-1}. The IRGA was calibrated weekly during the 1994 and 1995 operation periods using a zero gas of N_2 and 1000 µmol mol^{-1} CO_2 span gas (Scott Specialty Gases, Plumsteadville, PA, USA). The span gas was calibrated against a standard traceable to a National Bureau of Standards primary CO_2 standard (Scott Specialty Gases, Plumsteadville, PA, USA). The zero gas was checked by passing the gas stream through a CO_2 scrubbing column. No change from zero CO_2 was ever detected in the N_2 zero gas. The output signal from the analyser could be read with a resolution of 1 µmol mol^{-1}. Any changes which may have occurred to the absolute [CO_2] signal as the air sample passed through the sampling tubing were below the accuracy of the analyser and not discernible from normal instrument variability. [CO_2] readings from the IRGA were read at 1-s intervals. However, due to smearing of the sample within the 10 m long sample tube and 10 cm detector cell, the 1-*s*-values are reported as 'grab-samples', representing an averaging time of less than 4 s. The recorded [CO_2] during spikes or pulses in [CO_2] are less than their actual value to a magnitude depending on their duration. However, spikes lasting 6 s or longer would appear with recorded peaks which were at least 86% of their true value.

Data acquisition system. An enclosure containing a data acquisition and control subsystem (Opto22, Huntington Beach, CA) is located adjacent to the FACE array, and processed commands received on a fibre optic link from the control computer (see following section). The commands either requested measurements from sensors (input) or changed the state of a field device (output). Analog inputs included [CO_2] at the control point at 9 m height in the canopy at ring centre, ambient [CO_2], wind speed and direction, CO_2 mass flow rate, air temperature, atmospheric pressure, humidity, and either PAR (photosynthetically active radiation) or global solar radiation. The measurement of ambient [CO_2] was made at a point about 200 m south-west of the FFP. Digital inputs included the status of power supplies, fan rotation, and CO_2 pressure. A bi-directional DC motor controller positioned the Kurz CO_2 flow metering valve to provide the desired gas flow. Digital output signals turned the fan and the CO_2 feed line quarter-turn valve on or off and actuated 32 pneumatic pilot valves (Humphrey Products Co., Kalamazoo, MI) which in turn opened or closed the butterfly valves at the base of each vertical vent pipe.

CO_2 control system. It is not possible to achieve control of [CO_2] by simply making its release directly proportional to wind velocity due to a number of factors. Principal causes of variation in transport and mixing are air turbulence, low wind speed and other factors such as time delays in the system. For this reason, a custom control program was written which accommodates complex interactions between the sampling and control hardware. To optimize the operation of the control program, an extensive operator interface is provided which allows the system operator to view both the present and historical operation of the system in either textual or graphic modes. This interface allows the operator to adjust the integration and weighting functions of the control algorithm from the keyboard, so that the system can be fine-tuned as needed during the experiment while the control system is operating. Provisions were also made for data backup onto removable media, reporting alarms, and accessing the control program from a remote terminal.

The FACE control computer was an Intel-80386 processor-based personal computer located in a trailer remote from the FACE ring. This computer collected information from sensors and set devices in the field. A duplex fibre optic serial cable network (International Fiber Systems Inc., Brookfield, CT) was the only data link between the FACE control computer and the field. The primary purpose for using fibre optics was to electrically isolate

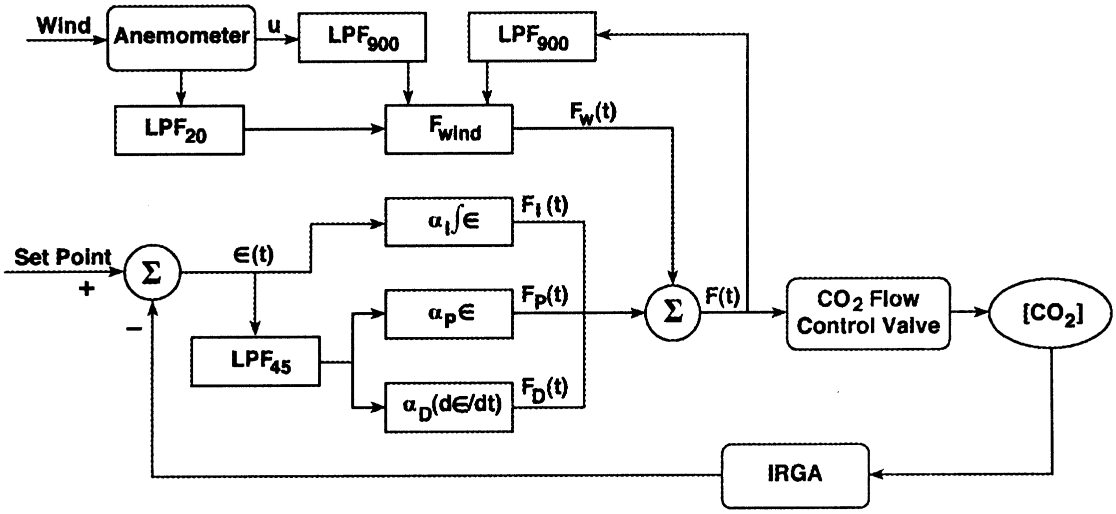


Fig. 3 FACE control algorithm schematic. Terms of the algorithm are in square boxes and are defined in the text. Round-edged boxes denote instruments receiving and/or sending signals to the control computer.

the trailer from the FACE arrays and the arrays from each other in event of lightning strikes, which are common in summer in central North Carolina. The computer controls the amount of CO_2 metered into the air stream entering the plenum based on wind speed and gas concentration sampled at the centre of the array. An empirically derived, proportional-integrative-differential (PID) control algorithm modified from that described in Lewin *et al.* (1994) and described below adjusts the amount of CO_2 introduced into the plenum. Another algorithm, which considers both wind direction and speed, controls which vent pipes emit this CO_2 enriched air (Lewin *et al.* 1994). These two algorithms work together to maintain the desired concentration within the central area of the FACE array while minimizing CO_2 usage.

The control program collects input signals from various sensors and uses this information to formulate output signals which control the fumigation system. Digitized signals from the wind sensors, the CO_2 flow controller and the CO_2 analyser located at the FACE array are passed by the fibre optic serial link to the FACE computer. These signals are the inputs to the modified PID algorithm (Fig. 3) which has the form:

$$F(t) = F_I(t) + F_P(t) + F_D(t) + F_W(t), \qquad (1)$$

where *F(t)* represents the output signal to the CO_2 flow controller at time *t*. The first three terms are a standard PID algorithm using negative feedback. F_I, F_P, F_D represent the parts of the total flow control signal supplied by the integral, proportional and differential components of the algorithm, respectively. The first term, F_I, is typically the dominant one. It represents the long-term CO_2 demand due to changes in vertical dispersion, wind speed, emitting port configuration, and array diameter. The next two terms, F_P and F_D, represent short-term adjustments whose sign and size depend on the magnitude and sign of the control error, and the rate at which the error is changing. In this study, a low pass filter with a 45-s time constant was used to prevent the control system from chasing very short-term variations. The last term, F_W, is not part of a standard PID algorithm, but is a feed-forward term designed to anticipate changes in gas demand due to changes in wind speed. This is accomplished by accumulating 900-s averages of wind speed and gas demand and releasing more or less gas depending on whether the short-term average wind speed is greater or less than the long-term average. There is a scaling coefficient, α, for each of the three PID components which allows the operator to change the relative contributions of each component in the algorithm.

The integral component, F_I, is defined as follows:

$$F_I(t) = F_0 - \alpha_I \int_0^t \varepsilon(t)dt, \qquad (2)$$

where F_0 is an initial set point value set at startup, α_I is the scaling factor for the integral component, and the control error $\varepsilon(t)$, is the difference between the actual gas concentration and the set point at time *t*. α_I is the scaling factor for the integral error component.

The proportional component F_P is computed by:

$$F_P(t) = -\alpha_P L_\tau(\varepsilon(t)), \qquad (3)$$

where α_P is the scaling factor for F_P, and L_r a low pass filter with a time constant of τ seconds. Application of the low- pass filter to a new signal $x(t')$ is defined by the convolution integral as:

as: $$L_r(x(t)) = \int_0^t x(t')e^{-(t-t')/\tau}dt', \qquad (4)$$

where t' is the next time step of measurement.

The differential component F_D is defined as:

$$F_D(t) = -\alpha_D L_\tau(d\varepsilon(t)/dt), \quad (5)$$

where α_D is the scaling factor for the differential component, and $d\varepsilon(t)/dt$ represents the rate of change in the control error.

Finally, the wind speed component F_W is calculated as:

$$F_W(t) = L_{900}(F(t))\,[L_{20}(u(t)) - L_{900}(u(t))]/[L_{900}(u(t)) + a_W] \quad (6)$$

where $u(t)$ is the wind speed at time t, and $L_{20}(\cdot)$ and $L_{900}(\cdot)$ represent the low pass filter evaluated at $\tau = 20$ s and $\tau = 900$ s, respectively. The term a_W accounts for the fact that gas demand is not strictly proportional to wind speed. Some gas input would be required even at zero wind speed due to diffusion and vertical dispersion of the gas out of the experimental plot area.

CO_2 distribution monitoring. A computer-controlled, multiple port, selectable-sequencing sampler (MP3S) customized from commercially available components (Hendrey *et al.* 1993) was set up to collect [CO_2] data from 68 sample ports arranged in four layers at 1, 3, 6 and 9 m elevation within the controlled experimental area, a cylindrical volume of 5309 m^3 (10 m height, 26 m diameter). The outer 2 m zone of the 30 m diameter FACE ring was considered a mixing zone in which experimental [CO_2] is not explicitly controlled. Samples were drawn sequentially from each port through a manifold of 3-way valves. A 15-s purge time was used between sequential samples, followed by a 45-s observation period. Delays due to travel time in the MP3S sampling system were $\approx$ 7 s. The manifold valves sequentially diverted a sample air stream to an IRGA (Binos, Leybold-Heraeus, Germany) separate from that used to control [CO_2] in the FACE array. This system, like the control IRGA system, results in a gas sample averaging time of < 4 s.

Results

Performance of the Forest FACE system

The FFP system was operated 6 June to 31 August 1994 and 23 May to 14 October 1995 with the target set-point CO_2 concentration of 550 μmol mol^{-1} (Fig. 4). In 1994, the system operated 12 h per day, and in 1995 the exposure period was lengthened to include all daylight hours from civil dawn to dusk. System reliability, defined as the fraction of scheduled treatment time that the system operated normally to the extent that fumigation control was provided ('up time'), was 96.7% of scheduled hours in 1995. On 8 full days in the 1995 operating season, the FACE system was deliberately not operated

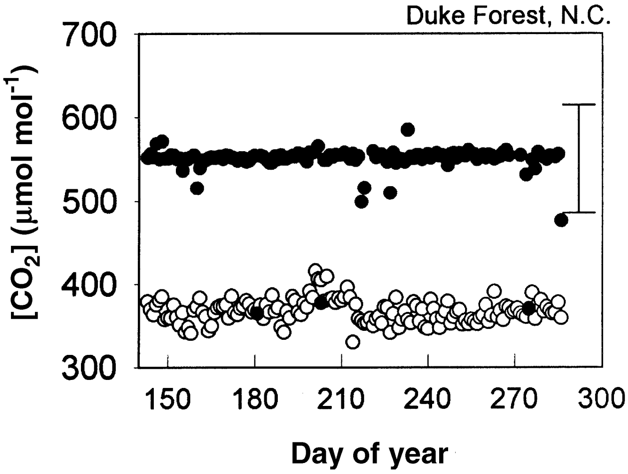


Fig. 4 Seasonal course of daily average ambient [CO_2] (○) and daily average [CO_2] at 9 m height in the centre of the FACE plot (●) during the 1995 operating period of 23 May–13 October. The data are for all times of planned operation of FACE and therefore include periods when the FACE system was not operating due to inclement weather or equipment failure. The bar at right indicates the average standard deviation of 1-min mean elevated [CO_2] across all days of scheduled operation.

in order to permit eddy-correlation measurements of whole-stand net CO_2 exchange (e.g. Katul *et al.* 1997a). To avoid damage to instruments due to lightning strikes, operation of the FACE system was suspended on a few occasions when severe thunderstorms were in the vicinity.

Summer conditions in this region of North Carolina (Fig. 5) are dominated by potentially difficult control conditions for an open-air system, such as low wind speeds (< 1 m s^{-1}), warm daily maximum temperatures (> 30 °C), and strong insolation driving vertical turbulence. During 1995, daily average wind speed ranged from 0.7 to 3 m s^{-1}, with over half of the operating season characterized by winds < 1.3 m s^{-1}. The predominant wind direction at the site during summer months was south-westerly, but variable. An example of a typical time course of diurnal data from the system (Fig. 6) shows some of the diurnal variability in wind speed and FACE operation characteristic of summer conditions at the Duke Forest site. A thunderstorm accompanied by increased winds (> 2 m s^{-1}) occurred at ≈ 21.00 hours on 10 July and the rapid change in wind speed was accompanied by a brief spike in [CO_2]. Another prominent spike in [CO_2] occurred on the following evening at dusk when windspeed dropped below the stall-speed of the anemometer (Fig. 6). The FACE system described here has the capability of tracking ambient [CO_2]$_a$ although this operating mode was not employed in the FFP experiment so as to facilitate performance analyses without a shifting target [CO_2]. Night-time ambient [CO_2] above 450 μmol mol^{-1} at the top of the canopy was a

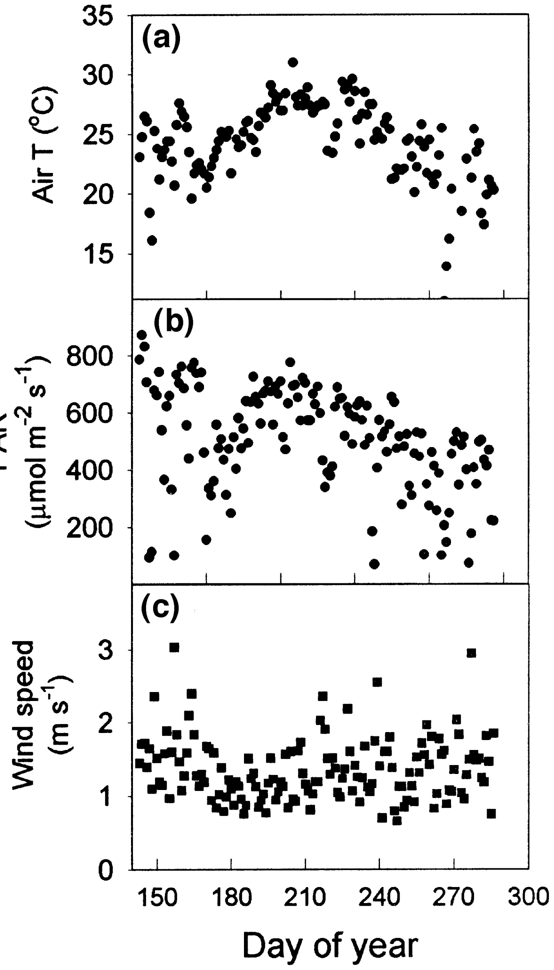


Fig. 5 Ambient environmental conditions for the forest FACE system Duke Forest, NC, during the 1995 operating period. Variables shown are those that are most important in affecting CO_2 use by the FACE system. Seasonal course of (a) daytime average temperature, (b) average daily PAR, and (c) daytime average windspeed at the top of the canopy measured at the FACE plot.

common feature at this site during summer when wind speed and turbulence were low (Fig. 6).

Performance averages

Daily average [CO_2] at the control point in the FFP varied by as much as 50 µmol mol^{-1} (Fig. 4), although daily averages deviating more than – 20 µmol mol^{-1} from the set point were due to unanticipated shut downs of the system caused by equipment problems or inclement weather. In 1994, the average [CO_2] at the control point in the centre of the ring was 549 µmol mol^{-1} for at least 10 h over 82 out of 88 possible days of operation. The average value at the control point over the 133-day operating period in 1995 was 552 µmol mol^{-1} (daily sd = 9 µmol mol^{-1}), similar to the 550 µmol mol^{-1} set point. An *a priori* goal for acceptable performance was that the 1-min average [CO_2] measured at the control point in the centre of the FACE plot remain within ± 20% of the set point (i.e ± 110 µmol mol^{-1} CO_2) at least 80% of the time. This goal was an arbitrary value thought to be both attainable from a technical point of view, and stable enough so as not to introduce significant biological responses due to the variability *per se*. The biological criteria for acceptable performance are considered most important for defining system performance in FACE experiments, and both spatial and temporal variability in treatment [CO_2] should be minimized as much as possible. In 1994, the 1-min average [CO_2] was within ± 20% of the 550 µmol mol^{-1} set point for 95% of the time and the distribution of these values was approximately normal (data not shown). In 1995, the 1-min average [CO_2] at 10 m above the soil surface at the centre of the FACE plot remained within ± 10% of the 550 µmol mol^{-1} set point for 69% of the time, and within ± 20% of the target 92% of the time (Table 1). The 5-min average values are also approximately normal (Fig. 7), and 98.8% of the values were within 10% of the set point.

Instantaneous ('grab') samples

Grab-sample [CO_2] values, each actually representing a 4-s average of instantaneous concentrations sampled each second at the control point and recorded once each minute (Fig. 7), are decidedly skewed with a steep cutoff at the ambient [CO_2]$_a$ (about 360 µmol mol^{-1}). The high-end tail extends to over 1000 µmol mol^{-1}, indicating that brief 'excursions' of [CO_2], while rare, were observed at the centre of the ring during the 1995 season. An excursion is defined to occur when [CO_2] is outside of some specified concentration range, beyond 10% of the target [CO_2] for instance. The frequency and duration of unusual excursions of [CO_2] are of special interest since they may be indicative of poor control of [CO_2] by FACE and thus might stimulate a biological response different from the response to the average CO_2 treatment. The data acquisition system was modified to record grab sample [CO_2] values continuously during four discrete periods of operation lasting a total of just over 17 h, or > 50 000 total observations. These periods represented both high and low wind conditions (> 2 m s^{-1} and < 1.5 m s^{-1}, respectively) during daytime. Fewer than 0.01% of all the measurements stored over this period represented excursions that both deviated from the target by more than 55 µmol mol^{-1} and persisted more than 60 s. Of all the [CO_2] excursions that were > ± 10% outside of the target, less than 2% lasted longer than 60 s. In the rare instances when [CO_2] excursions outside of ± 20% of the

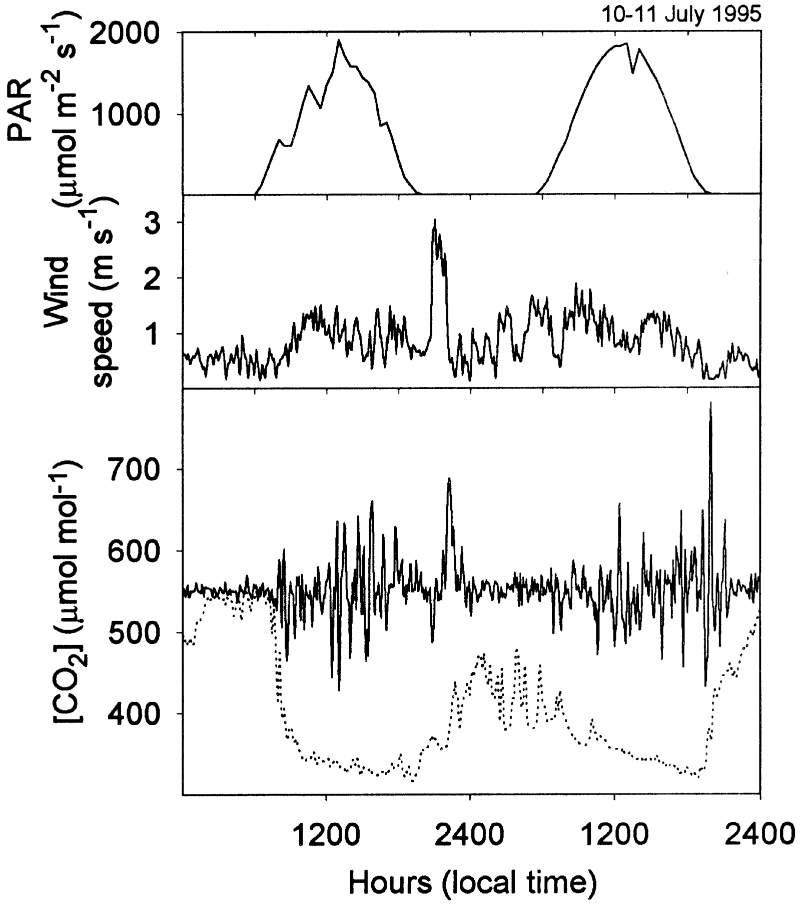


Fig. 6 FACE operation under typical summertime conditions at Duke Forest, North Carolina, USA. Data are shown for 12–13 July, a representative 48-h period during which the FACE system was operated in the continuous mode (both day and night). Upper panel: 30-minute average photosynthetically active radiation (PAR) measured above the canopy. Middle panel: 10-minute average windspeed measured at the top of the canopy. Lower panel: 10-minute average ambient $[CO_2]$ (dashed line) at 9 m height in the canopy at a location not influenced by FACE CO_2, and 10-min average $[CO_2]$ at 9 m height within the canopy at the centre of the FACE plot (solid line).

Table 1 Average monthly windspeed and percentage of observations of $[CO_2]$ in FACE within discrete performance classes for the grab sample, a near-instantaneous value of $[CO_2]$, and the 1-min integral of $[CO_2]$. Data are from the 1995 growing season during daylight hours (dawn to dusk). Performance classes are the percentage of records within ± 10% of the target $[CO_2]$ of 550 µmol mol^{-1} (e.g. values between 495 and 605 µmol mol^{-1}), and percentage within ± 20% of the target $[CO_2]$.

Month	Wind speed (m s^{-1})	Number of records	Grab sample $[CO_2]$within ± 20%	1-min integral$[CO_2]$ within ± 10%	within ± 20%
May	1.57	7674	65.1	74.5	94.2
June	1.45	24955	63.6	71.3	93.0
July	1.16	24340	58.6	64.0	90.0
Aug.	1.42	21077	60.8	67.8	92.1
Sept.	1.32	19718	62.9	70.0	92.5
Operating season	1.35	97764	61.7	68.7	92.1

target occurred, less than 0.5% of these lasted more than 60 s (Fig. 8).

Spatial control of $[CO_2]$

Immediately downwind of the emitter ports, CO_2 distribution is dominated by strong concentration gradients. Turbulent mixing of the jet with ambient air reduces perceptible jet speed to the speed of the ambient air within about 100 jet diameters. Since the jets are 2.5 cm in diameter, mixing is accomplished within a mixing zone that is about 2.5 m deep. In this zone, CO_2 concentration drops from 30 000 µmol mol^{-1} at the jet, to near the target concentration of 550 µmol mol^{-1}. Beyond this mixing zone, spatial distribution throughout FACE plots is decidedly nonuniform in the short run (Hendrey *et al.* 1993). In order to both evaluate this variability and to incorporate the data into the control program, it is important to obtain samples with as little temporal averaging as possible. Various sampling schemes were evalu-

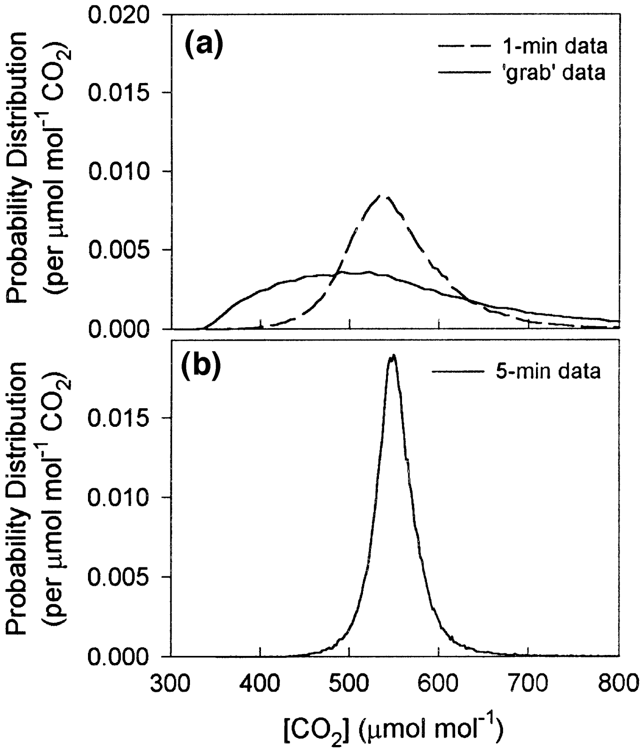


Fig. 7 Probability distributions of $[CO_2]$ measured at the control point in the centre of the FACE plot during the 1995 operating period of 23 May–13 October. Curves represent the same total frequencies. (a) Distributions of grab sample $[CO_2]$ and 1-min average $[CO_2]$ recorded during the entire operation period. (b) Distribution of 5-min average $[CO_2]$ over the period.

ated in the design of FACE, including combining samples collected from multiple sample points in order to average over the exposure area. Such averaging obscures the actual short-term variability, making FACE CO_2 control appear to be better than it is. The approach taken here was to provide control from a single sampling point. This point was determined imperically so as to minimize concentration variability throughout the three-dimensional volume of FACE plot over the long-term. Indeed, determining the proper placement of the control point was one of the reasons for building the forest prototype FACE system. To evaluate the actual conditions of plant exposure to elevated CO_2, information is also needed on the spatial distribution of CO_2, and that was obtained from the multiport sampling system (MP3S).

The MP3S continuously monitored CO_2 within the FACE plot during the 1995 operating season, in four horizontal planes. The data were displayed in real-time as concentration surfaces on a 2D plane. For the entire operating season, mean $[CO_2]$ values for each of the 68 points were in the range 495–710 µmol mol^{-1} corresponding to a range of – 10% to + 29% of the target $[CO_2]$ value of 550 µmol mol^{-1}. Most of the experimental area

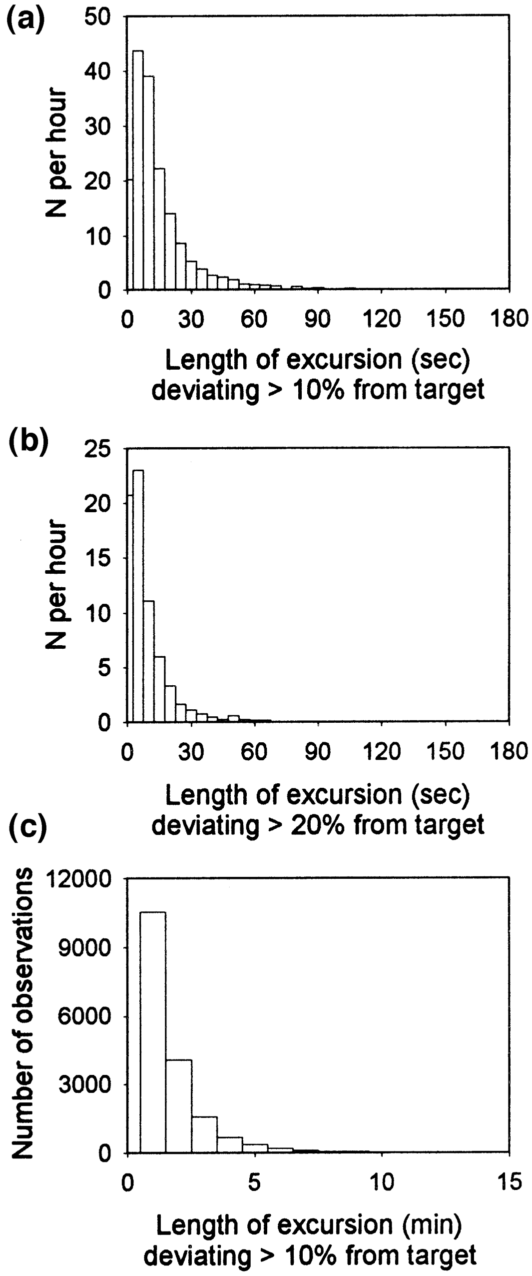
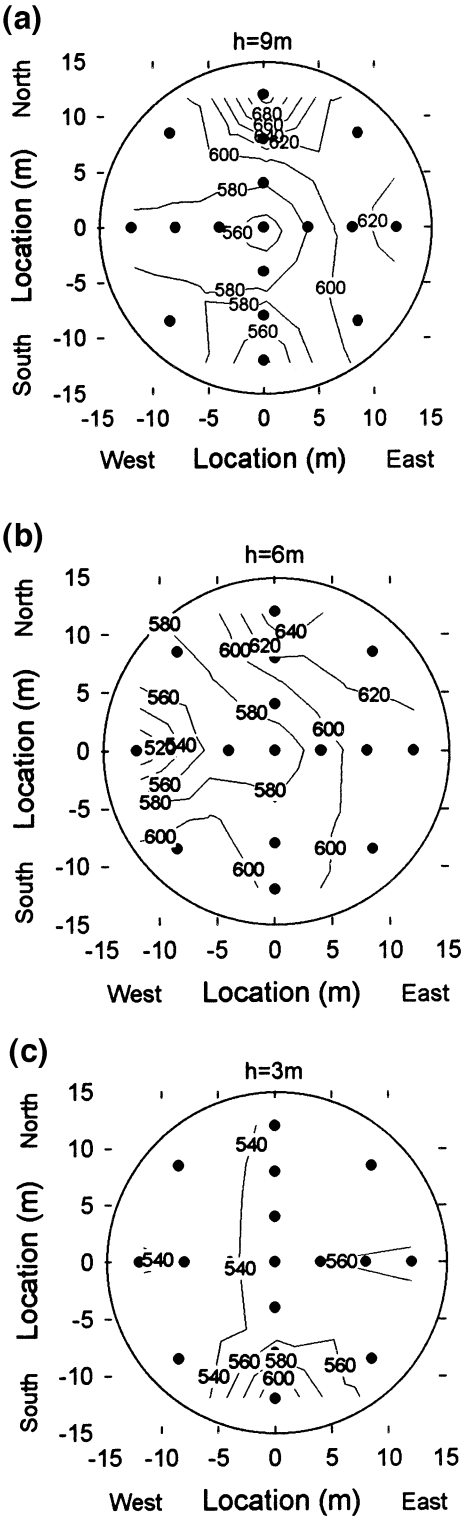


Fig. 8 Number and duration of $[CO_2]$ excursions (± s.d. from target $[CO_2]$) occurring per unit time in FACE at 9 m height at the centre of the plot. Two types of data are shown: grab sample data are for four discrete periods in June and August totaling over 17 full hours of continuous 1-s data, while 1-min data are from the entire operating period (May–Oct). (a) Average number of excursions per hour of $[CO_2]$ for grab samples deviating by > 55 µmol mol^{-1} (± 10% of target) from the CO_2 set point. (b) Average number of excursions per hour of $[CO_2]$ for grab samples deviating by > 110 µmol mol^{-1} (± 20% of target) from the CO_2 set point. (c) Number of excursions per day of $[CO_2]$ for 1-min averages deviating by > 55 µmol mol^{-1} (± 10%) from the CO_2 set point over the entire period.

within the FACE plot, represented by 63 points out of the 68 monitoring nodes, was within ± 20% of the target [CO_2]. Because of the interest in the CO_2 exposure regime of the understorey and canopy vegetation, spatial variability in the seasonal mean [CO_2] was analysed for 3 layers (height = 3, 6 and 9 m) corresponding to the upper branches of the dominant pine trees (9 m height), the layer corresponding to the base of the live crown for these trees (6 m height) and near the crowns of the understorey hardwood trees (3 m height). Data obtained in this way assisted the operators of the FFP in determining an optimal configuration of open or closed holes in the VVPs at different heights. These changes were made manually, a fairly time-consuming process, several times over the period of testing. The MP3S allowed an immediate evaluation of the effectiveness of these adjustments. Through repeated adjustments, it was possible to configure the emission ports to accommodate long-term, seasonal changes in airflow and stability at different canopy heights. No attempt was made to adjust the system to accommodate short-term changes in stability, i.e. diurnally.



Out of the 16 monitoring points at the 9 m height in the FACE ring (excluding the control point at the centre of the ring), mean [CO_2] values at 13 of these points representing ≈ 80% of the experimental area at this level (530 m^2) were within ± 10% of the target [CO_2] (Fig. 9a). A small portion of the experimental area at this level diverged from the target [CO_2] by more than 20% (north side of ring in Fig. 9a), and the standard deviations of the 1-min means were also highest for these points. At the 6 m height in the FACE ring, there is a similar gradient in [CO_2] means across the plot, with the 'hot spot' of just over 20% over the target [CO_2] located in the NE quadrant of the ring. The gradients across the plot at 9 m and 6 m are aligned downwind of the predominant wind direction from the SW (Fig. 9b). At the 3 m level within the forest understorey, [CO_2] values were most homogeneous over the plot area and with the exception of a single point (Fig. 9c) they were all within a few percentage of the target [CO_2].

CO_2 use in FACE

Consumption of CO_2 in FACE systems is closely related to ambient windspeed, but can also be influenced by atmospheric stability and incident radiation load (Nagy

Fig. 9 (a) Isolines of [CO_2] at 9 m above the ground showing spatial variability within the FACE experimental area for the daytime operating period of 1995. The large circle on the graph represents the perimeter of the zone of the vent pipes, with the zone of [CO_2] control beginning 2 m inward from the VVPs. The points represent the nodes for continuous monitoring of [CO_2] over the exposure season. (b) Isolines of [CO_2] at 6 m above the ground for the daytime operating period. (c) Isolines of [CO_2] at 3 m above the ground for the daytime operating period.

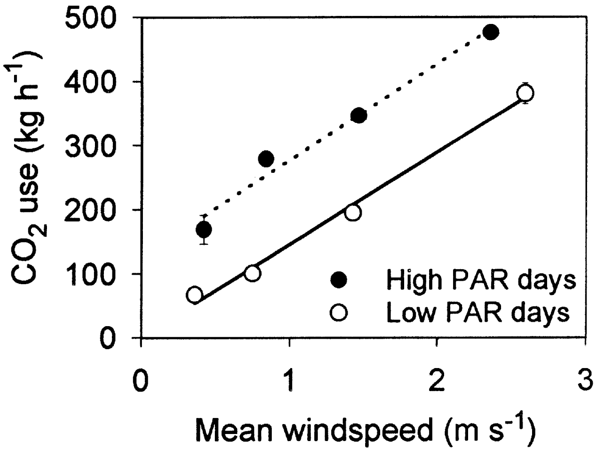


Fig. 10 Average hourly daytime CO_2 use as a function of daily average wind speed for the FACE prototype in 1995 during periods of high insolation (high photosynthetically active radiation, PAR; ●) and low insolation (low PAR; ○). High PAR was defined as days where average daytime PAR > 500 μmol m^{-2} s^{-1}, and low PAR was for days when average PAR < 450 μmol m^{-2} s^{-1}. Data are from hourly means aggregated by daily wind speed classes for the entire 1995 operating season. Vertical bars are standard errors and are obscured by the data points in most cases. Average slope of both lines is 147 kg h^{-1} m s^{-1} windspeed.

et al. 1994). In the FFP system, average CO_2 use was directly related to average wind speed (Fig. 10), with a distinct relationship for sunny ('high PAR') and cloudy days. Photosynthetically active radiation (quantum sensor, Li-Cor, Lincoln NE), a proxy for vertical convective turbulence in the forest plot had a large influence on gas use by the FFP system at all measurable windspeeds (Fig. 10). High gas-use at low windspeeds on sunny days compared to cloudy days could be attributed to this convective mixing which can result in vertical transport of CO_2 out of the FACE plot before enriched gas parcels reach the ring centre. The average demand for CO_2 under the conditions of the 133-day period of 1995 operation was 260 kg h^{-1}, or 50 g CO_2 h^{-1} m^{-3} of forest volume. Operationally, daily CO_2 use over the 1995 season varied from 1.4 to 6.5 tonnes day^{-1} for the FFP ring as verified by the flow meter in the ring and the actual CO_2 deliveries to the site. CO_2 use varied depending on wind speed and turbulence conditions (Fig. 10), with a mean of 3.4 tonnes day^{-1} over the May to October operating period.

Discussion

The FACE approach allows CO_2 enrichment experiments to be conducted in the field under actual climate conditions while manipulating atmospheric trace gases (e.g. Hendrey *et al.* 1993). FACE facilities developed by the authors at multiple sites (Maricopa, Arizona; Eschikon, Switzerland; Mercury, Nevada; Cedar Creek, Minnesota; and Rhinelander, Wisconsin) now provide useful and reliable research platforms for studying the effects of elevated atmospheric CO_2 levels on plant growth in open-field settings with low-stature vegetation (meadows, wheat and cotton; Hendrey *et al.* 1993; Nagy *et al.* 1995). The general design of the FACE systems used in these facilities, with low stature vegetation, should serve equally well for an establishing tree plantation until the trees become more than about 3 m tall. The purpose of the FFP effort at Duke Forest was to design, build and test a FACE system that can be applied to taller vegetation, including maturing forests.

The development of the FFP proceeded from experience gained in the design, construction and operation of the other FACE facilities. To see how this previous experience contributed to the design of the FFP, it will be helpful to provide a brief discussion of prior research activities (details are published elsewhere; Lipfert *et al.* 1989, 1991, 1992). Much attention was given to the engineering and testing of the gas injection and transport of FACE systems of the type described here (FACE rings greater than 10 m diameter). The performance of preceding FACE systems with respect to control of CO_2 concentrations and efficiency of CO_2 use and their application to biological field experiments is also extensively reported (e.g. Hendrey 1992; Dugas & Pinter 1994; Hebeisen *et al.* 1997). Physical engineering studies preceding the FFP included partial scale models of sections of the FACE system in which operating conditions such as fan pressure could be varied at will, air pressure and flow through the orifices measured, and gas distribution could be visualized with smoke releases. Engineering simulation models were constructed to examine and evaluate the behaviour of physical models operating at different fan pressures, injection port configurations, and ambient wind speed and turbulence regimes. Gas dispersion modelling with field verification based on data obtained from both the scale models and full-scale FACE facilities also was carried out.

Simulation modelling was conducted to cover three types of regimes. The 'jet regime' included fluid-dynamic models of air passing from the jet orifices in the VVPs and operated over a scale of centimetres to a few metres. This work helped to size the orifices of the injection ports, to evaluate an optimal angle for the triplet of jets at the same level on a particular VVP, and to determine the spacing among both jet orifices and VVPs. The second regime, called 'FACE-scale', covered the intersection of jets over the scale of 1 m to 30 m down wind of the emitter orifices, including simultaneous tracking of multiple jets entering a cross-flowing air current and the eventual intersection of these jets in a theoretical three-dimensional volume. For the third regime, a Gaussian dispersion model was used to analyse down-wind distribution of gas from the calculated, upwind, virtual emission point, in order to evaluate spacing of FACE plots in a particular area. These three models were linked in the following way. The jet-regime model tracked each jet out to a predetermined downwind distance, e.g. 2 m. This provided inputs for each jet to the FACE-scale simulation in which the plane of intersection was determined and, from that, the upwind virtual emission point calculated. The Gaussian model then used the virtual emission point for downwind dispersion modelling.

The suite of dispersion models was used as the basis for the first engineering design of the FFP built at the Duke Forest site in 1993. The behaviour and control of the first model of the FFP were 'pretty good'. Despite the availability of these theoretically based models, this empirical testing showed major design shortcomings. The system was re-scaled and rebuilt in the configuration described above.

Because this was the first controlled experimental exposure of a mature forest ecosystem in its natural setting to elevated CO_2 an intensive study was conducted to evaluate the effects of the FACE fan and air injection system on air stability and movement within the plot. Several sonic anemometers were deployed in this test. The anemometers were arrayed horizontally across the plot or vertically to capture changes in structure of the profile. These studies demonstrated that FACE exposure in the FFP was not accompanied by any biologically significant alteration of the forest microenvironment under a wide range of conditions (He *et al.* 1996).

The FFP system was able to maintain 1-min average $[CO_2]$ to within $\pm$ 10% of the set point at the centre of the FACE plot (Figs 4, 6) and to within $\pm$ 20% of the set point throughout nearly the entire experimental volume of the FFP plot (26 m diameter $\times$ 10 m high; Fig. 9). Thus the free-air CO_2 enrichment approach can achieve levels of control that equal or exceed those of open-top chambers (cf. Whitehead *et al.* 1995) in a ground area more than 10-fold larger, and in a volume more than 2 orders of magnitude larger than those typically exposed in open-top chambers. The sufficiency of control can be attributed to the rapid feedback control system that constantly adjusts the CO_2 injection rate in FACE according to parameters of the control algorithm, to predilution of CO_2 in ambient air prior to release, as well as to minor, longer-term tuning by manually adjusting the vertical distribution of CO_2 release ports on the VVPs. System control of the FFP was evaluated in terms of adequacy of long-term $[CO_2]$ at the control point, spatial variability in $[CO_2]$ throughout the exposure volume, and persistence of short-term $[CO_2]$ fluctuations (CO_2 excursions). The long-term $[CO_2]$ regime defined as day-to-day variability (standard deviation) around the target $[CO_2]$ at the ring centre was only 9 μmol mol^{-1} in 1995 (Fig. 4), the spatial variability (sd) in seasonal $[CO_2]$ among 68 sampling points in the FFP was 48 μmol mol^{-1}, and only 3% of the 1-min CO_2 observations that deviated more than $\pm$ 10% from the target $[CO_2]$ also were longer than 5 min in duration (Fig. 8c). Collectively, these statistics suggest that a large-scale field FACE system in a complex, tall-forested ecosystem can operate for long periods of time with an acceptable CO_2 exposure regime for elevated CO_2 research in forests. This is the first time that an elevated CO_2 experiment has been conducted under true forest conditions (on a plantation forest soil, with an actual forest canopy, and in an intact forest ecosystem). Adequate CO_2 control and sufficient characterization of the $[CO_2]$ regime in the experimental plot is central to conducting an elevated CO_2 experiment in an actual forest ecosystem and for assessing the carbon storage responses of forest vegetation under futuristic conditions.

Comparable performance data are not available for many other CO_2 exposure systems since $[CO_2]$ is frequently measured with extended signal averaging or by passing the air stream through a buffer volume before measuring $[CO_2]$. Clearly, with increasing averaging times the $[CO_2]$ distribution data converge more closely on the mean (Fig. 7), and the FACE $[CO_2]$ distribution data are similar to those shown for open-top chambers (Lee & Barton 1993; Norris *et al.* 1996). In contrast to the automatic control system used in FACE, open-top chamber experiments sometimes rely on manual adjustment of CO_2 injection rates to control the system (Ashenden *et al.* 1992; Whitehead *et al.* 1995), and the long-term $[CO_2]$ variability can diverge from the target $[CO_2]$ for many days if the system is not adjusted frequently. In at least one open-top chamber study involving trees, the hourly average $[CO_2]$ was so variable that $[CO_2]$ within $\pm$ 10% of the target value could not be achieved more than 50% of the operating time (Wang *et al.* 1995). In contrast, open-top chamber and screen-aided CO_2 enrichment experiments employing some kind of feedback algorithm exhibit much better $[CO_2]$ control (Norris *et al.* 1996; Leadley *et al.* 1997). In our FACE system, a rapid computer feedback control system, predilution of CO_2 prior to release into ambient air, and directional control of CO_2 release points around the circular array enhance $[CO_2]$ control and hence system performance while minimizing gas use. The degree of $[CO_2]$ control can be an important issue since physiological responses of trees to elevated CO_2 vary on time scales from seconds to years (Eamus & Jarvis 1989; Saxe *et al.* 1998), and many such responses are nonlinear over a wide range in $[CO_2]_a$.

Short-term variability in $[CO_2]$ can be larger for unconfined, free-air systems than for chamber systems since FACE relies on ambient wind for CO_2 transport. Short-term variability on the order of minutes can be important for some physiological responses to CO_2 such as stomatal closure, although stomatal responses of a C_3 crop to 3-

min fluctuations of $[CO_2]_a$ did not produce a different response from the time-averaged mean response (Cardon *et al.* 1994). Moreover in forest trees, stomatal responses to CO_2 are much slower than for crops, with larger lags and a smaller amplitude of response (Ellsworth *et al.* 1995; Saxe *et al.* 1998; Ellsworth, unpublished data). This does not mean that the apparatus of photosynthesis is unresponsive to short-term changes in $[CO_2]$. A recent study employing rapid step excursions in $[CO_2]$ showed that *in vivo* fluorescence of photosystem-II can respond to a step-change within 2 s of the change. However, electron transport measured by modulated chlorophyll fluorescence was insensitive to $[CO_2]$ excursions lasting 60 s or less (Hendrey *et al.* 1997). Hence, net photosynthetic and stomatal responses of trees are unlikely to be manifest with rapid CO_2 excursions lasting less than a minute, such as those that may be produced in FACE. Excursions of $[CO_2]$ outside of the $\pm$ 20% criterion range in the FFP do occur (Fig. 8b) but they are of short duration, with less than 0.7% of recorded excursions lasting as long as a minute and none lasting more than 100 s. The 1-min average $[CO_2]$ values were symmetrically distributed about the mean so that there was no high or low bias in plant fumigation at this period of averaging (Fig. 7).

Performance of the FFP under summer conditions was not as good as shown for previous FACE experiments in short-stature vegetation during summer (e.g. Nagy *et al.* 1994; Miglietta *et al.* 1997). This can partly be ascribed to environmental conditions, since the average windspeed at the Duke Forest site is lower than at either the Maricopa FACE facility or the Eschikon Swiss FACE facility (compare 1.35 m s^{-1} at Duke Forest to 1.6–1.7 m s^{-1} and 1.5 m s^{-1} at the other two sites, respectively). However, the primary reason for differences in performance in the FFP compared to crop FACE systems is that the FFP must control $[CO_2]$ within a much larger exposure volume than for short-statured vegetation, in vegetation with a more complex canopy geometry, and in plots with a much smaller canopy height to ring diameter ratio (3:1 in FFP compared to ratios of 10:1 for crops; He *et al.* 1996). The heterogeneous nature of turbulence in forest canopies compared to crop canopies (e.g. He *et al.* 1996; Katul *et al.* 1997b) is also responsible for the differences in performance between crop and meadow FACE experiments and the current FFP experiment. Sweep and ejection eddy motion near the top of the canopy makes it increasingly difficult to control CO_2 throughout the vertical profile of a forest in increasingly taller stands, and can result in higher CO_2 use in a nonuniform forest than in crop systems because of CO_2 loss by vertical transport. Even so, the prototype FACE system described here achieved close-to-target $[CO_2]$ at three forest strata (Fig. 9).

CO_2 use is often a critical issue in free-air experiments because of the costs involved in handling and using large amounts of CO_2 in large field plots. CO_2-saving measures such as organ-level chamber enclosures ('branch-in-bag' approach, Lee & Barton 1993; Teskey 1995) are highly economical in terms of low overall cost although CO_2 use per unit chamber volume is often higher in branch chambers than in FACE, and the very small exposure volume limits the investigations that can be undertaken. It appears unlikely that the physiological responses measured at this scale are quantitatively similar to those of tissue subjected to whole-tree CO_2 exposures (Saxe *et al.* 1998). Moreover, use of any enclosure can alter the thermal and light environment of the plants within. Such changes in microenvironment are undesirable and can affect the CO_2 responses observed (Drake *et al.* 1989; Ashenden *et al.* 1992). Enclosure effects on trees may even be larger than those of the desired CO_2 treatment (Ceulemans *et al.* 1994; Murray *et al.* 1996).

Possible effects of elevated CO_2 on biological processes within the FACE plot were not addressed directly in the present study. The lack of significant microenvironmental effects (He *et al.* 1996), however, is encouraging in that FACE technology was developed in order to avoid experimental artifacts inherent in the use of controlled-environment chambers, glasshouses, open-top chambers, etc. Yet, some issues regarding use of FACE for forest experiments remain to be resolved. For example, the minimum and maximum size of FACE plots have not been determined. In applying FACE in natural forest settings, it may be important to have plots larger than the 30 m diameter plots described here, to accommodate heterogeneous communities. As another example, strategies for FACE experiments may include daylight-only operations as in the present work, or 24 h per day operation. There is some evidence that net diurnal respiration is reduced when $[CO_2]$ is elevated at night (Bunce 1990, 1992, 1995). Whether or not daylight-only operation creates an artifact related to nocturnal respiration is the subject of much discussion as it involves a trade-off between a cost-reduction strategy (reduced CO_2 use) and maintenance of experimental reality. This topic may require additional research to determine if suppression of nocturnal respiration does occur in natural field settings. If it does, and if the suppression leads to a significant gain in carbon diurnally, this might suggest that FACE experiments should be run to provide elevated $[CO_2]$ on a 24-h basis.

While the seasonal exposure described here was conducted over a range of temperature and wind conditions (Fig. 5), the performance and gas-use data do not comprise the full range of annual conditions for this site. A new, fully replicated set of FACE arrays with a similar design to that described here have recently been constructed in the same forest and are now under full-year operation in the $[CO_2]_a$ tracking mode. We conclude that based on several performance criteria such as adequacy of long-term $[CO_2]$, spatial homogeneity in [CO_2] in the exposure volume, and the short nature of [CO_2] fluctuations (CO_2 excursions), exposure of a tall forest plot to elevated CO_2 for ecophysiological and ecosystem-level experimentation over the growing season is tractable using the FACE approach. The FACE exposure system described here, with appropriate modifications, is also suitable for use with other atmospheric trace gases such as O_3, SO_2, and NO_x.

Much has been learned from the FFP that can be of use in designing FACE experiments for forest settings, and some improvements might be made to our present design. For example, it may not be necessary to use the relatively expensive aluminium towers on large, concrete bases, for experiments with lower-stature forests. A simpler set of wooden poles may suffice. Since the FFP was primarily an engineering study, steps to minimize impacts on understorey vegetation were not a rigorous as they might have been for a biological experiment. Decisions were made early in the development of the FFP concept, to focus on the engineering primarily, rather than on the biological responses to testing of the apparatus as a means of holding developmental costs down. Nevertheless, very useful biological observations have been made (Ellsworth *et al.* 1995). Future designs should pay more attention to infrastructure that minimizes impacts on the experimental setting and vegetation and perhaps more biological information can be obtained along side the engineering activity. The modelling effort used to develop the FFP could be extended to help refine FACE engineering design tools and experience gained from the present version of the FFP should be incorporated into the suite of FACE engineering models. The present study, however, demonstrates that in this field of experimental design-engineering (as is well known in virtually all engineering disciplines) investment in a prototype is a critical step in development of new technology, or extension of existing technology into a new application.

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