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Informal Report

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Enrichment Forest Prototype - Interim Report

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August 1994

Biosystems and Process Sciences Division

MASTER

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**Brookhaven National Laboratory Free-Air Carbon Dioxide
Enrichment Forest Prototype - Interim Report**

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I. INTRODUCTION

A. Background

A variety of approaches have been used in fumigation experiments to quantify the effects of increasing atmospheric carbon dioxide concentration ($[\text{CO}_2]_{\text{atm}}$) on plants. Most of these approaches, reviewed elsewhere (Allen 1992), entail some type of enclosure or chamber. Chambers provide containment of the CO_2 -enriched air and in this way reduce the amount of CO_2 required for the experiment. At the same time, chambers alter microclimate conditions in a variety of ways so that there is a significant "chamber effect" on the plants within. 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 $[\text{CO}_2]_{\text{atm}}$ without causing any change in other environmental variables.

Early types of free-air exposure systems were built in the Netherlands (Mooi and van der Zalm 1985) and England (McLeod et al. 1985) for exposing vegetation to elevated concentrations of atmospheric trace gases. The FACE Program at Brookhaven National Laboratory (BNL) considered these original ideas in designing the BNL FACE systems. Some of the innovations added by the BNL program that have resulted in effective regulation of $[\text{CO}_2]_{\text{atm}}$ within FACE experiments included (1) continuous, on-line computer regulation of gas concentration using feedback control technology; (2) fast feedback regulation of the fumigation system without in-line volumetric averaging; (3) greater pre-dilution of CO_2 to about 3% prior to release into the ambient air; (4) increased directional control around a circular fumigation system including inverse cosine correction, or "feathering", of the release at tangents about parallel to wind direction; (5) adjustment of the release height according to plant height and vertical wind speed profiles; (6) extensive, three-dimensional monitoring of $[\text{CO}_2]_{\text{atm}}$ throughout the FACE plot volume and use of these data for control of the fumigation; (7) real-time, on-line analysis of FACE system control; (8) use of redundant components, stocking of spare parts, and intensive preventive maintenance to assure highly reliable performance; (9) remote, on-line access to the control system via modem coupled with call-up error-state notification to

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assure operator attention on a 24-hour basis; and (10) the "user facility" concept, in which a large community of scientist-users participates in operational decision making.

B. BNL FACE Systems in Operation

At the present time, there are two fully operational FACE user facilities that have been designed, assembled, and operated by BNL and these are the models from which the FACE Forest Prototype system is developed. The first of these is now operated by the USDA/ARS Water Research Laboratory (Phoenix, AZ) at the Maricopa Agricultural Center of the University of Arizona (MAC), and the second by the Institute for Plant Sciences, Swiss Federal Institute of Technology (ETH), Zurich. These FACE systems have proven to be able to control CO_2 very well and to be highly reliable. In the cotton experiment of 1989-91, the 1-min. average $[\text{CO}_2]$ was held to within $\pm 20\%$ of the set point better than 97% of the time over all three seasons. Season-long average $[\text{CO}_2]$ measured at 72 points throughout the area and volume of the plot (ground to canopy top) varied by 3.3%. None of the MAC FACE systems was out of operation for more than 1% of the planned experimental period. The ETH FACE system is able to control $[\text{CO}_2]_{\text{atm}}$ about as well as the MAC FACE, with similar reliability. In 1994 alone, over a hundred scientists from ten nations participated in FACE experiments at these two facilities.

C. BNL/Duke FACE Program Objectives

The purpose of the current BNL project in the Duke Forest is to develop a FACE system that can provide adequate control over $[\text{CO}_2]_{\text{atm}}$ in a tall forest setting. FACE system already have been shown to provide reliable and acceptable control over $[\text{CO}_2]_{\text{atm}}$ for vegetation of up to 2m in height during seven seasons of experimental operation (five at MAC, two at ETH). The question addressed by the present project is: **Can FACE provide adequate control over $[\text{CO}_2]_{\text{atm}}$ in a tall forest canopy?** This is an important question to consider if FACE experiments, starting with seeding of a cleared field and continuing for a decade or more, are contemplated.

It is reasonable to assume that a FACE system can provide a similarly reliable and well controlled experiment for a regenerating forest for as long as it takes the forest to reach a height of at least 2 meters. But, as the vegetation increases in height, so does the volume of the experimental plot. If $[\text{CO}_2]_{\text{atm}}$ 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 concentration. Also, as canopy height (h) increases, it becomes more difficult to control CO_2 throughout the vertical profile because of the non-uniform character of the wind profile within the canopy.

II. Duke Forest Site Description

The BNL FACE Forest Prototype is located in the Blackwood Division of the Duke Forest, Chapel Hill, NC. This section of the Blackwood Division is on farm land abandoned a century ago. The old field became a forest that was clearcut in 1979, drum-chopped and burned in 1980 and planted with loblolly pine (*Pinus taeda*) in 1981. Now, the forest of the Blackwood Division is dominated by loblolly pine with 537 stems per acre, but with large numbers of sweet gum (*Liquidambar styraciflua*) at 244 stems per acre and yellow poplar (*Liriodendron tulipifera*) at 120 stems per acre, as indicated in the attached site botanical survey. The loblolly are about 10 m tall in the summer of 1994 and increasing in height at about 1 m/yr.

An extensive soil survey was conducted by Richter for Brookhaven National Laboratory in 1993 in order to describe the FACE plot and this part of the Blackwood Division (Appendix I). All of the soils are of the Enon series and, according to Richter, are typical of upland soils of the Southeast.

III. Description of the FACE Forest Prototype System

Major sub-components of the FACE Forest Prototype (FFP) include (1) the CO_2 supply system, (2) the fan and plenum system, (3) the vertical vent pipe system, and (4) the control system.

A. CO₂ Supply

Carbon dioxide is obtained as a by product of manufacture of agricultural fertilizer from natural gas and atmospheric nitrogen. The CO₂ is cleaned to food-grade and liquefied for highway transport in lots of up to 19 tons. It is delivered to the FACE site and transferred to a 26-ton receiver. Tank pressure is maintained at about 1725 kPa (250 psig) to keep the CO₂ in a liquid state. A refrigeration unit and a heater maintain this pressure regardless of demand. Under normal operation, liquid CO₂ is fed to heat exchangers which vaporize the CO₂ as needed.

Liquid CO₂ is vaporized using a combination of solar and electrical heat. The gaseous CO₂ is channeled through 5-cm internal diameter (ID) piping to a pressure regulator that reduces line pressure to 138 kPa above ambient (20 psi). The regulator is equipped with a manually actuated shut off valve and there is an electrically actuated shutoff valve at the FACE ring. The CO₂ gas, now under low pressure, is piped out to the FACE array through 5 cm ID polyethylene tubing.

The CO₂ is throttled by a rotary ramp valve (Kurz model 735) that provides a very even, linear gradation of gas flow over the range 0 to 1,550 kg hr⁻¹ (0-520 SCFM). The Kurz valve is regulated directly by the FACE control computer (described below). The CO₂ is then injected into the plenum just down stream of the air supply fan.

B. Fan and Plenum

Two models of the FFP were built at the same location at the Duke site. These differed in capacity of the fan, placement of the main distribution plenum, and diameter of the plenum and VVP pipes. FFP Model-1 (FFP-1) was assembled in the summer of 1993 and operated until September 16, 1993. Data obtained from FFP 1 were used to re-design the system. The fan, plenum and VVPs of FFP-1 were removed and FFP-2 was built in the spring of 1994. The plenum was removed from within the FACE plot of FFP-1 and an entirely new plenum was assembled outside of the circle of VVPs in FFP-2 in order to minimize the impact of the equipment on vegetation within the study area

1. FFP Model-1:

The circular air handling system of FFP-1 (Figure 1 (not included at this time)) was made of 30-cm diameter PVC pipe arranged in a torus with a diameter of 10 m centered in the 30-m diameter forest plot. A radial fan (Buffalo Forge, Model 35-V) placed just outside the plot drew in ambient air and injected it into the plenum at a rate of about 30 m^3 per minute with a pressure of about 1.2 kPa (4.8 inches H_2O) above ambient. This provided a continuous, even flow of air via a 30-cm diameter duct to the plenum. Pure carbon dioxide gas from the Kurz valve, regulated by the FACE computer, was injected into the outlet of the fan. The average enrichment of this air in FFP-1, prior to release from the VVPs was about 12% CO_2 . The CO_2 -enriched air passed from the fan to the plenum via a 25-cm diameter polyethylene pipe (Hancor Hi-Q).

2. FFP Model 2

The radial fan (American Fan Co., Model BC5-165) of FFP-2 (Figure 2 (not included at this time)) provided air flow at the rate of $102 \text{ m}^3 \text{ min}^{-1}$. The plenum was a 34-m diameter torus made of 38-cm diameter polyethylene pipe (Hancor Tite-Line) connected to the fan at a "T" by a 2-m length of the same pipe.

C. Vertical Vent Pipes

1. Upwind control

Thirty-two vertical vent pipes (VVP) were evenly spaced around the circumference of the 30-m diameter FACE plot (Figure 3). Normally, the VVPs were opened or closed so as to provide release of CO_2 -enriched air from the upwind direction only. This feature reduces the waste of CO_2 that would occur if it were released on the down wind side and reduces the potential for carry-over of CO_2 among adjacent plots.

2. Feathered edges

Since CO_2 -enriched air is released from a semi-circle of VVPs there is a potential for excessive CO_2 concentrations to occur near the edges of the plot with

tangents parallel to wind direction. Therefore, a "feathering" of the VVPs is achieved by keeping the second VVP from each end of the arc of 12 upwind VVPs closed (10 VVPs open).

3. Low wind speed regime

Detection of true wind direction becomes unreliable with the Climatronics wind vane at wind speed less than 0.4 m s^{-1} . Therefore, when wind speed drops below that threshold for a 20-second average, directional control is given up and every other VVP around the FACE ring is opened. This is the most problematic condition for maintaining control of CO_2 concentration because (1) transport from the VVP into the plot is very irregular in all three axes; (2) low wind speed means that transport of the CO_2 -enriched air from the VVP to the sample intake for the control IRGA in the center of the plot is slowed, increasing feedback delay; and (3) parcels of air differentially enriched with CO_2 move irregularly through the plant canopy and may move back into the same FACE plot.

4. Towers

For both models of the FFP, two VVPs were suspended from each of sixteen 12 m tall aluminum towers (Universal Manufacturing Co.) evenly spaced around the perimeter of the 30-m diameter plot (Figure 3). These towers had a triangular profile 76 cm per side at the base, and are set into a base of 5 m^3 of concrete. The towers are free standing and can be climbed. They may be extended in height to 20 m without guying, and considerably higher if guyed.

5. VVP valves

Pneumatically-actuated butterfly valves (Figure 4) with an internal diameter of 10 cm and each separately controllable, opened or closed the VVPs according to wind direction averaged over a 10-second period. Each valve was connected to a manifold of 32 pneumatic valves actuated by the control electronics with 12-volt DC solenoids. The pneumatic system was pressurized at 90 psi with CO_2 from the high pressure side of the CO_2 supply system.

6. Vertical distribution of emitters

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 to achieve optimal three-dimensional distribution of CO₂.

7. Differences between the FFP-1 and FFP-2 VVPs

a. FFP-1

Sixteen polyethylene (Hancor Smoothwall) pipes of 10-cm diameter were connected to the plenum and evenly spaced around its circumference. Each of these pipes led outward to a horizontal "T" and then to two VVPs. The 32 VVPs were evenly placed around the periphery of the 30-m diameter FACE plot. Air flow to each of the VVPs was separately controlled by the FACE computer through the butterfly valve at the base of each VVP.

The thirty-two VVPs made of 7.6-cm diameter polyethylene pipe were suspended from a horizontal cross arm attached to each of the peripheral towers at a height of 10.5 m. Each VVP had 1.27-cm diameter emitter ports arranged in sets of three at 0.5-m vertical distances from a height of 0.5 m to 9 m. The ports were placed in horizontal groups of three arranged so that the middle port was centered radially on the center of the circular array, with the adjacent ports angled from the center port in the same plane by 60 degrees on each side.

b. FFP-2

The thirty-two 15-cm diameter polyethylene VVPs were suspended from the same towers and in the same manner as for FFP-1. 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. Emitter ports of 2.5-cm diameter were arranged in triplets in a similar way to those in FFP-1. The triplets were spaced at 0.5-m vertical intervals from 2 m above the ground to the top of the pipe.

D. CO₂ Control system

Regulation of CO₂ concentrations within the FFP and registration and logging of all pertinent data are achieved via a set of fully integrated subsystems consisting of the following: (1) wind and CO₂ detectors; (2) data acquisition system; (3) CO₂ control computer and data management system; and (4) CO₂ distribution monitoring system.

1. Wind and CO₂ detectors

Wind speed is measured near the top of the canopy by a sensitive cup anemometer (Climatronics model 100076) and wind vane (Climatronics model 101871) mounted on one of the VVP towers. The minimum detectable wind speed is 0.3 m sec⁻¹ and the wind vane is reliable at wind speeds above 0.4 m sec⁻¹.

A non-dispersive infrared CO₂ gas analyzer, or IRGA (Siemens Ultramat model 21P), at the center of the FACE plot continuously monitors the gas concentration at a control point within the canopy. Air is sampled from the center of the array, with the inlet height set just above the height of intersecting branches among the trees (7 to 9 m). The sampled air is pumped at 2.5 l/min through approximately 10 meters of 4.3 mm ID polyethylene tubing before it reaches the analyzer. The time for the sample to traverse this distance, along with measurement delays inherent in the analyzer, results in a total delay of 10 to 12 seconds between when the air sample enters the sampling tube and when the resulting concentration is delivered to the control program.

The Siemens IRGA has an accuracy of 1% of its full scale range of 0-1000 $\mu\text{mol mol}^{-1}$, or 10 $\mu\text{mol mol}^{-1}$. The output signal from the analyzer can be read with a resolution of 1 $\mu\text{mol mol}^{-1}$. Any changes which may have occurred to the absolute carbon dioxide concentration as the air sample passed through the sampling tubing were well below the accuracy of the analyzer and not discernible from normal instrument variability.

Samples were actually reported from the IRGA at 1-second intervals. However, due to smearing of the sample within the 10-m long sample tube and 10-cm detector

cuvette, the 1-second values are reported as "grab-samples", representing an averaging of less than 4 seconds

2. Data acquisition system

The FACE computer is an Intel-286 processor-based personnel computer located in a trailer remote from the FACE ring. This collects information from sensors and sets devices in the field. A duplex fiber optic serial cable network (International Fiber Systems Inc., Brookfield CT) is the only data link between the FACE control computer and the field. The primary purpose for using fiber optics is to electrically isolate the trailer from the FACE arrays and the arrays from each other.

Adjacent to each FACE array in the current BNL design is an electronics enclosure containing an Optomux data acquisition and control subsystem (Opto22, Huntington Beach CA) which processes commands received on the fiber optic link from the control computer. The commands either request measurements from sensors (input) or change the state of a field device (output). Analog inputs include $[CO_2]$ at the control point, ambient $[CO_2]$, wind speed and direction, CO_2 mass flow rate, air temperature, atmospheric pressure, humidity, and either PAR or global solar radiation. (Not all measurements need be made at all arrays at all BNL FACE sites.) Digital inputs include the status of power supplies, fan rotation, and CO_2 pressure. An analog channel is used to provide a set point signal to the CO_2 mass flow proportional valve controller (Kurz Instruments, Monterrey CA). Digital outputs turn the fan and the CO_2 feeder quarter turn valve on or off, and control automated IRGA calibration systems. Another bank of 32 digital outputs actuates pneumatic valves (Humphrey, Kalamazoo MI) which in turn open or close the butterfly valves at the base of each vertical vent pipe.

3. CO_2 control computer and data management

The amount of CO_2 metered into the air stream entering the plenum is based on wind speed and gas concentration sampled at the center of the array. An empirically derived, proportional-integrative-differential (PID) control algorithm adjusts the amount of test gas introduced into the plenum. Another algorithm,

which considers both wind direction and speed, controls which vent pipes emit this CO₂ enriched air. These two algorithms work together to maintain the desired concentration within the central area of the FACE array while minimizing CO₂ usage. Minimizing CO₂ usage reduces not only operating costs but also the probability of contaminating adjacent treatment and control areas

It is not possible to achieve acceptable control of CO₂ by simply making its release directly proportional to wind velocity, due to the time delay between release of the CO₂ at the mass flow controller and its distribution within the control area of the array, and due to variations in ambient turbulence. For this reason, a custom control program was written which allows complex interactions between the sampling and control hardware. 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. The operator can also adjust many of the integration and weighting functions from the keyboard, so that the system can be fine tuned while operating and adjusted as needed during the experiment. Provisions are also made for data backup onto removable media, reporting alarms and accessing the control program from a remote terminal.

The control program collects input signals from various sensors and uses this information to formulate output signals which control the fumigation system. Analog signals from the wind sensors, the CO₂ flow controller and the CO₂ analyzer located at the FACE array are passed to an interface board in the FACE computer. These signals are the inputs to the PID algorithm which has the form:

$$F_{total} = F_{integ} + F_{prop} + F_{diff} + F_{wind}$$

where:

$$F_{integ} = F_{integ} - a_{integ} * e = F_0 - a_{integ} \int_0^t e \, dt$$

$$F_{prop} = -a_{prop} * L_t(e)$$

$$F_{diff} = -a_{diff} * L_t(de/dt)$$

$$F_{wind} = L_{900}(F_{total}) * [L_{20}(u) - L_{900}(u)] / [L_{900}(u) + a_{wind}]$$

In these equations, F_{total} represents the output signal to the CO_2 flow controller. F_{integ} , F_{prop} , F_{diff} and F_{wind} represent the parts of the total flow control signal supplied by the integral, proportional, differential and wind speed (u) components of the algorithm. The difference between the actual gas concentration and the set point (error) is represented by " e ". The scaling factors a_{integ} , a_{prop} , a_{diff} and a_{wind} allow the operator to change the relative contribution of each component in the algorithm. L_t signifies a low pass filter with a time constant of " t " seconds applied to the argument.

The first three terms are a standard PID algorithm using negative feedback. The first term, F_{integ} , is the dominant one and 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_{prop} and F_{diff} , represent short-term adjustments. Their size and sign depend on the magnitude and direction of the error and the rate at which the error is changing. A low pass filter with a 45-second time constant is used to prevent the control system from chasing very short term variations.

The last term, F_{wind} , is not part of a standard PID algorithm. It anticipates changes in gas demand due to changes in wind speed. The software accomplishes this by accumulating 15-minute averages of wind speed and gas demand. More or less gas is released depending on whether the short term average wind speed is greater or less than the long term average. The a_{wind} parameter 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.

4. CO_2 distribution monitoring

A multi-port selectable sequencing sampler (MP3S) was set up to collect gas concentration 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 4,072 m³ (9 m high, 24 m diameter).

IV. FFP SYSTEM PERFORMANCE

FFP-1 was tested in late summer of 1993. The system was then rebuilt as FFP-2 in order to increase the pre-dilution of CO₂ prior to release from the VVPs. Throughout the operation of both FFP-1 and FFP-2, numerous experiments were carried out in order to find optimal configurations and algorithm settings. For this reason, the data reported here represent less than the best control that may be achievable with the FFP.

A. Performance Analysis for FFP-1

The FFP-1 system was run periodically over the summer of 1993 in a test mode to gather information on how to make FACE experiments work in a tall forest setting. Data were obtained from over 800 hours of operations under a wide range of wind speed and turbulence conditions. As a part of our engineering studies the vertical configuration of emitter ports and the target gas concentration were varied in order to analyze and improve overall system performance. The FACE control algorithm was also tuned in order to improve performance under the various test conditions.

1. Test period

By the end of the summer the FFP-1 system was operating reasonably well and a 5-day test was conducted over the period 13-17 September in which no further modification were made to any of the system configuration. One of the ideas of this test was to observe the ability to control [CO₂]_{atm} under varying climate conditions. Average hourly wind speeds during the period 13-17 September 1993 measured 12 m above the forest floor at the FFP varied from calm to above 2.5 m/s (Figure 5). Weather was variable with cloudy periods in which there was minimal vertical turbulence to sunny, still periods in which the control was dominated by vertical transport.

2. Performance averages

The 1-minute average of [CO₂]_{atm} measured at the control point at h = 7 m in the center of FFP-1 was within 10% of the set point for 71% of the time and within 20% of

the set point for 94% of the time (Figure 6). Mean $[\text{CO}_2]_{1\text{m}}$ at the control point was very close to the set point of $550 \mu\text{mol mol}^{-1}$ (Figure 7) but the mode is slightly lower. CO_2 use was determined primarily by wind speed (Figure 8) and vertical turbulence (not determined) which is closely related to total insolation.

3. Spatial control

The multiport sampling system (MP3S) continuously monitored CO_2 within the FACE plot. Over this entire test period averages of the $[\text{CO}_2]_{1\text{m}}$ values for each of the 68 points were in the range 500 to $675 \mu\text{mol mol}^{-1}$ (Figure 9-12) corresponding to a range of -9% to $+22\%$ of the target value, $550 \mu\text{mol mol}^{-1}$.

The 1-minute CO_2 concentration averages for all 68 ports of the MP3S system were in the range $550 \pm 220 \mu\text{mol mol}^{-1}$ throughout the 1 m to 9 m elevation zone. However, the deviation of $[\text{CO}_2]_{1\text{m}}$ from the target concentration was not uniformly distributed. A significant gradient was observed from upwind to downwind.

4. Deficiencies of FFP-1

The strong downwind gradient was the result of inadequate pre-dilution of CO_2 prior to release from the emitter ports. FFP-1 released air with an average enrichment of $12\% \text{ CO}_2$. Based on the performance of other FACE systems and engineering studies of gas dilution within the FACE experiments, it was clear that the gradient could be greatly reduced by increasing the extent of pre-dilution of the CO_2 prior to release from the emitter jets. This could be accomplished by increasing the output of the fan by a factor of 4 to achieve a pre-dilution similar to that achieved in the MAC and ETH FACE systems. However, increasing fan output by a factor of 4 meant that all of the distribution piping, the plenum and VVPs, needed to be enlarged to handle the larger air flow.

C. Performance Analysis for FFP-2

1. Test period

The FFP-2 system was assembled in the spring of 1994 and was operated in a test mode through the summer. The system operated 12 hours per day with a set point concentration of $550 \mu\text{mol mol}^{-1}$. Data available at the time of this report include 38 days

of operation from 06 June through 13 July. This was a good test period in that it was dominated by the worst type of control conditions: lots of low wind speeds (Figure 20a,b) and strong insolation driving vertical turbulence. Wind direction was predominately southwesterly, but variable (Figure 21).

2. Performance averages

Despite numerous changes in variables such as the height of the emitter ports, the number of ports open at a particular level, the weighting coefficients of terms in the algorithm, and elevation of the intake port for the FACE control IRGA, the FFP-2 system performed quite well over all. Daily average $[\text{CO}_2]_{\text{atm}}$ at the control point (Figure 16) varied by as much as $10 \mu\text{mol mol}^{-1}$. The average value at the control point over the 38-day period was $548 \mu\text{mol mol}^{-1}$, 3% lower than the $550 \mu\text{mol mol}^{-1}$ set point. A primary criterion of acceptable performance is that the 1-min average $[\text{CO}_2]_{\text{atm}}$ measured at the control point in the center of the FACE plot remain within $\pm 20\%$ of the set point at least 80% of the time: it was within $\pm 20\%$ of the $550 \mu\text{mol mol}^{-1}$ set point for 95% of the time (Figure 17) and the distribution of these values was approximately normal. The 5-minute average values are also approximately normal and over 99% of them are within 10% of the set point (Figure 18).

3. Grab-samples

Grab-sample values, each actually representing a 4-second average of instantaneous concentrations sampled at the control point once each minute (Figure 19), are decidedly skewed with a steep cutoff at the ambient $[\text{CO}_2]_{\text{atm}}$ (about $360 \mu\text{mol mol}^{-1}$). The high-end tail extends to over $1000 \mu\text{mol mol}^{-1}$.

4. Persistence of excursions

An "excursion" occurs when $[\text{CO}_2]_{\text{atm}}$ is outside of some specified concentration range. All of the grab-sample records were saved during seven discrete periods of operation lasting a total of 6 hours 23 minutes, or 22,980 observations. These were usually taken in hour-long increments throughout the period of observation. The lengths in seconds of excursions of $\pm 10\%$ and $\pm 20\%$ are shown in Figures 20 and 21. Less than

2% of the excursions outside of ± 10 lasted longer than 60 seconds. Less than 3% of the excursions outside of $\pm 20\%$ lasted as long as 60.

5. Spatial control

The 68 ports of the MP3S must sample sequentially. During the period of observation, a 15 second purge time was used between sequential samples, followed by a 15-second observation period. Averages over the test period for each of the four layers ($h = 1, 3, 6, 9$ m) are presented as contours in Figures 22-25. At $h=1$ m the entire area is within $\pm 10\%$ of the set point with a weak SE to NW decreasing gradient. At $h=3$ m about 80% of the plot area is within the 10% of the set point and there is a strong gradient in the remaining 20% of the area with all but a very small part to the south within 20% of set point. There is a similar gradient at 6m but with the "hot spot" of just over 20% located to the SW. All of the 9m layer is within 20% of the set point and about 80% is within 10%. The gradients across the plot at 9m and 6m are aligned with the predominant wind direction from the SW.

6. CO₂ use

CO₂ use was directly related to wind speed as can be seen in Figure 26. Much of the variability is associated with the various tests in which the emission configuration or algorithm were set at less than optimal states. The variability in vertical transport may also be an important contributor to variability in CO₂ use. The average demand for CO₂ under the conditions of this project over the 38-day period of operation was 344 kg per hour.

7. Extrapolation to large FACE experiments

Assuming that wind speed is higher in the cold months and vertical transport is lower, the rate of CO₂ use may be about the same as in summer, but this should be verified by analysis with seasonal wind data and by operation of the FFP in cold weather conditions. If a FACE experiment operated in this type of forest, with trees of the same height, and under the same general wind conditions, it would require about 4,100 kg CO₂ per 12-hour day for each FACE ring. Assuming one-third as much CO₂ is required for FACE operation at night, it would require 5,500 kg per 24-hour day. Operating 365 days

per year would require 1,500 or 2,000 metric tons of CO₂ per year for 12-hour and 24-hour operations, respectively. An experiment with 6 FACE arrays of 30-m diameter in 10-m tall forest would require 9,000 or 12,000 metric tons of CO₂ per year for 12- or 24-hour operation, respectively.

If a FACE forest experiment were initiated with seed plantings in a cleared field, daily CO₂ use would resemble that of the Arizona FACE experiment (scaled up) for several years, then gradually increase to the amount required by the FFP-2. The FACE systems in Arizona, if scaled up to 30-m diameter and applied to a low-stature, regenerating forest, would use 2,300 kg CO₂ per day (based on 1.5 m s⁻¹ average wind speed and a 12 hour day

V. CONCLUSIONS

BNL FACE facilities at MAC, Arizona, and at ETH, Switzerland, now provide useful and reliable research platforms for studying the effects of elevated atmospheric carbon dioxide levels on plant growth in open-field settings with low-stature vegetation. Although they have been used on meadows, wheat and cotton (a tree grown as an annual), they should work equally well for a tree plantation until the trees become more than about 3-5m tall. The purpose of the current research project at the Duke Forest is to design, build and test a FACE system that can be applied to taller vegetation, including maturing forests.

It was demonstrated by the FFP-1 experiment that the FACE system needed to be scaled up in size to accommodate trees of 8-10 m height. Specifically, the pre-dilution of CO₂ had to be maintained at about 3% on average necessitating a much large air handling system than was used in previous FACE facilities.

The FFP-2 system was able to maintain 1-minute average [CO₂]_{atm} to within ±5% of the set point at the center of the FACE plot, and to within ±20% of the set point throughout the entire experimental volume of the plot, 26m diameter x 9m high.

The 1-minute average [CO₂]_{atm} values were symmetrically distributed about the mean so that there was no high or low bias in plant fumigation at this period of

averaging. However, the grab-samples (4-second average values) are decidedly skewed. Excursions of $[\text{CO}_2]_{\text{atm}}$ outside of the $\pm 20\%$ criterion range do occur but they are of short duration, with less than 5% lasting as long as a minute and none lasting more than 95 seconds.

This report is a preliminary overview of the data and much remains to be done in the analysis. The data available from FFP-2 were obtained during the hot months and it is essential for a reasonably complete evaluation of the applicability of FACE systems to forests that data be obtained during the very different climate regime of the cold months.

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Appendix I

Soil Survey in the Blackwood Division

Conducted for

Brookhaven National Laboratory

July, 1992

by

Daniel D. Richter, Ph.D.

School of the Environment

Duke University

Figure 1. Schematic layouts of FFP-1 and FFP-2. Not included in this draft

Figure 2. Photograph of FFP-1 fan and plenum connection. Not included in this draft

Figure 3. Vertical vent pipes suspended from peripheral towers

Figure 4. Pneumatically actuated butterfly valves used for both FFP-1 and FFP-2, attached to the peripheral plenum of FFP-2.

Fig. 5 Hourly average windspeed at 12 m above ground in the FFP 13-17 Sept. 1993.

--- $\pm$ 10% of set point (includes 70.7% of data)
 $\pm$ 20% of set point (includes 94.2% of data)

Fig. 6 One minute average $[\text{CO}_2]_{\text{atm}}$ at 7 m elevation at the FFP control point 13-17 Sept. 1993.

Fig. 7. Frequency of 1-min. average $[\text{CO}_2]_{\text{atm}}$ at the FFP control point 13-17 Sept. 1993 (all fumigation data at control point, day and night).

Fig. 8 CO_2 use (—) and windspeed (---) at the FFP 13-17 Sept. 1993.

Fig. 9 Isolines of $[\text{CO}_2]_{\text{atm}}$ at 1 m above ground in the FFP 13-17 Sept. 1993 (0700-1700h).

Fig. 10 Isolines of $[\text{CO}_2]_{\text{atm}}$ at 3 m above ground in the FFP 13-17 Sept. 1993 (0700-1700h).

Fig. 11 Isolines of $[\text{CO}_2]_{\text{atm}}$ at 6 m above ground in the FFP 13-17 Sept. 1993 (0700-1700h).

Fig. 12 Isolines of $[\text{CO}_2]_{\text{atm}}$ at 9 m above ground in the FFP 13-17 Sept. 1993 (0700-1700h).

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

Figure 18

Figure 19

Figure 20

Figure 21

NC 6 June - 13 July 1994

[CO₂] 15-s average Z = 1m
Figure 22

NC 6 June - 13 July 1994

[CO₂] 15-s average Z = 3m
Figure 23

NC 6 June - 13 July 1994

[CO₂] 15-s average Z = 6m
Figure 24

NC 6 June - 13 July 1994

[CO₂] 15-s average Z = 9m
Figure 25

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FYI
DR

RECONNAISSANCE SOIL SURVEY OF YOUNG LOBLOLLY PINE STANDS OF THE BLACKWOOD
DIVISION OF DUKE FOREST

27 July 1992
Daniel D. Richter

A soil survey conducted by my students and I in 1991 has raised concerns about the regional representation of the soils that support young loblolly pine plantations on the Blackwood Division. The survey included a large open field adjacent to the pine stands of interest. Soils in the open field were found to include Iredell series, a soil with unusual physical and chemical properties.

Overview: The Blackwood Division of Duke Forest has several basic igneous sills on which Iredell series soils have formed, soils with unusual physical and chemical properties compared to the general conditions of upland soils in the southeast USA. Physically, Iredell soils are shallow, very rocky, very poorly aerated in subsoils, and are dominated by their highly plastic, heavy subsoils that are mainly montmorillonitic clay. Chemically, Iredell soils are Alfisols, high in pH and base saturation (often 100% base saturation at soil pH). Such neutral pH conditions are made possible by the high weathering releases of base cations from the base-rich rocks. Such edaphic conditions contrast with upland soil conditions in much of the southeast USA. Most of the uplands in the southeast are dominated by highly weathered, acidic Ultisol soils.

Much of the open field on the Blackwood that was surveyed in 1991 was found to be underlain by Iredell soil. It was natural to be concerned about the extent to which Iredell soils may underlie young plantations that surround the open field.

Soil Survey: On 27 July 1992 a field survey was conducted of young pine plantations that surround the open field of the Blackwood Division, in Management Compartments 4, 6, and 7. Most of the survey was devoted to plantations in compartments 4 and 7, to the west and north of the open field. The survey's primary objective was to determine the extent of Iredell soil series in these stands.

Five E-W transects were walked and four to five auger holes drilled per transect. Both surface and upper subsoil properties were observed. As is often the case, the SCS County Survey (Orange Co.) was found to be accurate in general, but inaccurate for the particulars of the site. A substantial area of Enon series soil was found in these plantations, far more than is mapped by the SCS survey. Iredell was found in Compartment 4 but is prevalent more to the west of where it is mapped by the SCS survey. In fact, most of the young stands in these two compartments (4 and 7) are thought to be supported by Enon rather than Iredell soils. Enon was also found in the large plantation in Compartment 6 that is directly north of the open field. No mapping of the plantation to the east of the field has been done.

Enon is a soil derived from igneous rocks but is derived from acid and basic rocks. Enon has a mixed clay mineralogy in contrast to Iredell's montmorillonitic clay. Enon is a deeper soil than Iredell; surface soils above the B horizon were found to be up to 40 cm in depth. Last and not least, Enon is more acidic than Iredell. Enon is classified as an Alfisol but is classified in

the Ultic subgroup of Alfisols. Enon is a soil on the borderline between Alfisols and Ultisols.

From my perspective, finding Enon instead of Iredell in these pine stands is good news. The plantations appear to be supported by soils that occur quite frequently in the southeast.

I would recommend that soils be carefully examined so as to guide the placement of the chambers on site. There were several areas in the plantation that are quite rocky and these should be avoided.

Compartment 6
Blackwood Division, Duke Forest
FACE Project

Plot	Sample Level	Soil pH- dry	Soil pH- KCl
C-1	A	6.07	4.95
	B	6.11	4.98
	C	6.16	5.08
C-2	A	6.14	5.07
	B	6.11	4.92
	C	6.07	4.71
N2-W2	A	5.57	4.60
	B	5.36	4.16
N2-W4	A	5.52	4.30
	B	5.54	4.30
	C	5.57	4.31
N2-W6	A	5.97	4.74
	B	6.01	4.85
	C	6.03	4.83
N2-W8	A	5.92	4.82
	B	5.90	4.85
	C	5.86	4.78
N4-W2	A	5.40	3.97
N4-W4	A	5.73	4.47
	B	5.87	4.29
N4-W6	A	5.82	4.45
	B	5.94	4.26
N4-W8	A	5.49	4.37
	B	5.57	4.39
	C	5.74	4.52
N6-W2	A	5.17	4.07
	B	4.94	3.52
N6-W4	A	5.95	4.99
	B	5.62	4.38
N6-W6	A	5.96	5.36
	B	5.64	4.54
	C	5.64	4.15

Dry pH			
Sample Level	# Samples	Mean	St. Dev.
A	13	5.75	0.29
B	12	5.72	0.34
C	7	5.87	0.23

KCl pH			
Sample Level	# Samples	Mean	St Dev
A	13	4.63	0.41
B	12	4.45	0.41
C	7	4.63	0.32