FC03-95NV62026
762 792

1 Submitted to
2 Tree Physiology

3

4 Title: Whole system carbon exchange of small stands of *Pinus ponderosa* growing at different
5 CO₂ concentrations in open top chambers.

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31 key-words: ponderosa pine, open top chambers, forest carbon balance, photosynthesis

32 ABSTRACT

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3 Functional understanding of the carbon cycle from the molecular to the global level is a high
4 scientific priority requiring explanation of the relationship between fluxes at different spatial and
5 temporal scales. We describe methods used to convert an open top chamber into both closed
6 and open flow gas exchange systems utilized to measure such fluxes. The systems described
7 consist of temporary modifications to an open top chamber, and are put in place for several
8 days on one or several open top chambers. In the closed system approach, a chamber is
9 quickly sealed for a short, predetermined time interval, the change in gas concentrations is
10 measured, then the chamber is unsealed and ventilated. In the open flow system approach,
11 airflow into the open top chamber is measured by trace gas injection, and the air stream
12 concentration of CO₂ and water vapor is measured before and after injection into the chamber.
13 The closed chamber approach can resolve smaller fluxes, but causes transient increases in
14 chamber air temperature, and has a high labor requirement. The open flow approach reduces
15 the deviation of measuring conditions from ambient, may be semi-automated (requiring less
16 labor), allows a more frequent sampling interval, but cannot resolve low fluxes well. Data
17 demonstrating the capabilities of these systems show that, in open canopies of ponderosa
18 pine, scaling fluxes from leaves to whole canopies is well approximated from summation of leaf
19 P_s rates. Flux measurements obtained from these systems can be a valuable contribution to
20 our understanding whole system material fluxes, and challenge our understanding of
21 ecosystem carbon budgets.

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1 INTRODUCTION

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3

4 Prediction of the potential effects of the increasing concentration of carbon dioxide in the
5 earth's atmosphere on plants requires experimental systems that allow long term treatment of
6 plants growing in realistic conditions, and systems that allow for in situ measurement of key
7 material fluxes such as carbon and water. Given their wide distribution (Dixon et al., 1994),
8 study of coniferous systems is important to our understanding of the consequences of
9 increasing CO₂ at the global level. Some evidence suggests that coniferous systems are
10 presently the most important terrestrial system for carbon sequestration (Tans et al.; 1990,
11 Taylor & Lloyd, 1992; Houghton, 1993; Dixon et al., 1994). Yet the study of conifers provide a
12 special challenge to the development of these measurement systems, because of their carbon
13 and water flux rates per unit leaf or ground area is relatively low. Cuvettes designed to enclose
14 and measure material fluxes from plants have been utilized now for several decades (Schulze
15 1972; Atkinson et al. 1986; Bingham et al, 1980; Field et al, 1989; Field et al.,1982), but the
16 scale of these measurements, taken at the leaf level, have left the difficult problem of scaling to
17 the system level unaddressed. This problem has been widely recognized (Körner, Amorr, &
18 Hilti 1993; Körner 1995; Norman, 1993; Baldocchi, 1993; Jarvis, 1993; Reynolds et al., 1993),
19 and there is a general trend to the measurement of carbon dioxide and water vapor exchange
20 of plant systems at the whole plant to small community level (Mordacq et al., 1991; Drake,
21 1992; Oechel et al.,1992; Daudet and Claustres, 1995; Ham et al. 1995; Livingston et al.,
22 1994).

23

24 The Forest Response to CO₂ project (Ball et al., 1991) was designed to compare ponderosa
25 pine (*Pinus ponderosa*) and loblolly pine (*Pinus taeda*) responses to varying CO₂ and nitrogen
26 treatments. Initial measurements of above ground carbon and water fluxes were made at the
27 leaf level, and from the whole seedling and branch level using a large cuvette system of our
28 own design (Ball et al. 1992). In the third year of the experiment fluxes became large enough
29 to resolve on a whole system basis. Our efforts to obtain whole system measurements
30 resulted in the experimental systems development described in this paper. Although the "eco-
31 systems" in the open top chambers are far from perfect representations of future forest
32 ecosystems, they do include the major processes, pools, and fluxes for carbon, water and

1 nitrogen that are characteristic of forest systems. The purpose of our whole system
2 measurements is to estimate the system carbon budget, and to examine the potential for a
3 budget developed by scaling lower level fluxes to the whole system. The scale at which these
4 fluxes are measured on CO₂ enriched stands in the field within this series of experiments likely
5 represents the limit for which experimental replication is possible, given economic and technical
6 constraints.

7

8

9 MATERIALS AND METHODS

10

11 *Site description*

12

13 An elevated carbon dioxide open top chamber field study site was established in Placerville
14 California at the US Forest Service's Institute for Forest Genetics in May of 1991. Twenty four
15 open top chambers were constructed to allow study of Ponderosa pine under three differing
16 atmospheric CO₂ concentrations (ambient, ambient +125 ppm, and ambient + 350 ppm) and
17 three differing nitrogen application regimes (control, + 10 g·m⁻², + 20 g·m⁻²). The trees were
18 watered daily during dry months utilizing an on site irrigation water delivery system (see Ball et
19 al., 1991, 1992; and Johnson et al., 1996 for further descriptions of experimental design and
20 experiment hypothesis).

21

22 During the winter/spring months in Placerville, warm sunny weather is punctuated with
23 occasional days of heavy wet snows and strong winds. Since significant photosynthetic and
24 respiratory activity can occur under these conditions, construction of open top chambers
25 capable of providing year round fumigation with minimal maintenance and economical
26 operating costs was essential to the experiment. The commonly used open top chamber
27 (Heagle et al., 1973) utilizing a 6 or 8 mil polyethylene film tied to a steel frame with a steel
28 cable draw string is prone to failure in winds of only 20-30 mph (Owensby et al., 1989). Thus
29 we developed an open top chamber specifically designed to withstand the expected site
30 conditions. The chambers were designed to allow 24 hour, year round fumigation with CO₂ at
31 three concentrations listed above.

32

1

2

3 *Utilities*

4

5 All utilities required at the chambers (water, CO₂ , electricity) were run underground to minimize
6 shading of the plant canopies. Water is first filtered, then flows through a timed normally closed
7 solenoid valve at a 7.62 cm diameter irrigation standpipe to a looped 2.54 cm diameter PVC
8 water main. The water then goes through a pressure regulator, finally to be delivered through
9 low pressure spray heads located in each open top chamber. A parallel, normally open
10 solenoid valve was installed at the standpipe in order to allow water to spray inside the open
11 top chambers in the event of a power failure. This strategy was intended to reduce the
12 potential for heat stress should a power outage cause fan failure during warm periods.

13

14 Carbon dioxide is stored as a liquid in a 12 ton receiver (TOMCO₂ Equipment Co., Loganville,
15 GA), vaporized and delivered at 300 psi to a heated regulator. The CO₂ then flows through a
16 normally closed solenoid valve to a looped 2.54 cm diameter PVC distribution manifold at 125
17 psi. Final delivery to each chamber is at 60 psi (see Rogers et al. 1983 for a typical CO₂
18 fumigation system description). Electrical power is run underground from a fused distribution
19 board by the site instrumentation trailer to panels distributed throughout the site.

20

21 *Open top chamber construction*

22

23 The overall construction of the open top chamber is illustrated in Fig. 1. Each chamber
24 consists of a 2.86 meter tall hexagonal steel, aluminum and wood frame glazed with twelve
25 1.22m x 1.68 m , 0.635 cm thick crystal clear acrylic sheet panels. These panels have a light
26 transmittance of 92% when tested per ASTM method D1003 (Acrylite FF, Cyro Industries, Mt.
27 Arlington, NJ). One of these lower acrylic panels is removable, allowing access into the interior
28 of the chamber. The dimensions of the hexagon are set to approximate the 3.0 m diameter of
29 the commonly used open top chamber (Heagle et. al. 1973). The open top chambers are
30 capped with a 25% open frustum glazed with trapezoidal 0.635 cm thick acrylic panels, the
31 frustum angle was set at 30 deg. off horizontal. This frustum design was chosen to minimize
32 incursions of ambient air into the open top chambers (Baldocchi et al. 1989).

1

2 The design of the open top chambers used at Placerville has now been proven over the four
3 years of site operation with no structural or glazing failures, despite exposure to severe winter
4 storms with strong winds and heavy snowfall. The only maintenance required by the chambers
5 has been to occasionally wash the acrylic panels, replace the air plenums, and clean the air
6 filters at the fan inlet..

7

8 *Air system*

9

10 Recognizing that operating costs for an open top chamber site is strongly influenced by the
11 cost of CO₂ , a unique, simple modification to the air delivery system was developed for the
12 Placerville field site. The rule of thumb for the operation of open top chambers is to provide
13 approximately three air changes per minute, which adequately compensates for the radiative
14 heat gain inside of the chamber. The absence of radiative heating at night allows for reduction
15 of air flow into the chamber, with minimum flows needed only for maintenance of plant dosing
16 with CO₂. Two speed blower motors are used to achieve the reduced night time flow rate
17 (Stanley model S-18, 1/2 hp, direct drive, two speed, 110V 1 ph., 0.46 m diameter propeller fan
18 mounted in a galvanized steel cabinet).

19

20 The fan motor speed (air flow rate) is controlled by a relay that switches between high and low
21 motor speed (day and night, respectively). The high/low air flow decision is controlled by a
22 photo cell and a twelve volt control circuit (Fig. 2). The CO₂ flow is also reduced when the low
23 flow decision is made. This is done concurrent with the air flow reduction to maintain the
24 chamber CO₂ dosing at a uniform concentration. The CO₂ flow reduction is achieved by
25 splitting the injected CO₂ flow into two components; a night time flow (always on), and a day
26 time flow, which is controlled by a solenoid valve. The solenoid valve allows the concurrent
27 shut-off of CO₂ when the fan speed is reduced (Fig. 3.). Air is delivered to the chamber at a
28 rate of 110 m³/min. during the daytime flow period, and at 67 m³/min. during the night time flow
29 period.

30

31 Air is distributed inside the open top chamber through a 0.01 cm thick, 46 cm diameter low
32 density polyethylene tube (McCalif Grower Supplies Inc., Ceres, CA). The plenum

1 (polyethylene tube) is perforated with 276 2.5 cm diameter holes distributed on 15 cm centers.
2 The system provides 2.7 air changes per minute when operating at high fan speed, and 1.6 air
3 changes per minute at low fan speed.

4

5 *Below ground isolation*

6

7 A below ground barrier consisting of a ten mil low density polypropylene film was placed in a
8 narrow vertical trench excavated to the Argillic horizon (approximately 0.6 m below the surface)
9 along the outside of the chamber perimeter. The trench was back filled with native soil after
10 placing the plastic barrier. The barrier was placed to isolate the tree's roots within the soil
11 volume confined by the Argillic horizon below the open top chamber. There are two reasons
12 that a soil volume is important; first, soil nitrogen was manipulated by the application of N as
13 ammonium sulfate, applied in early spring on the soil surface inside of the open top chamber,
14 and second, there is evidence of enhanced root growth in response to elevated atmospheric
15 CO₂ (Rogers et al., 1992), which we felt necessitated the confinement of the system within the
16 treatment area both above and below ground.

17

18

19 **CLOSED CHAMBER GAS EXCHANGE MEASUREMENTS**

20

21 Initial efforts in 1993 to measure whole system fluxes of CO₂ and water utilized the closed
22 system approach (see Field et. al., 1989 for a detailed description of this method applied at the
23 leaf level). The basic premise of this method is to seal the studied system inside a cuvette, and
24 observe the change in concentration for the gases of interest during a specified time interval.
25 Advantages of this method include the ability to obtain measurements of low fluxes, limited only
26 by the system leak to flux ratio. Disadvantages include radiatively induced temperature
27 increases during the study period, system induced artifacts in the measured signal (CO₂
28 response effects, stomatal aperture changes induced by rising relative humidity, and
29 temperature effects) and a high labor content due to the need to quickly seal and open the
30 chamber.

31

32 *Experimental Method*

1

2 The glazing seams and door panel were sealed to the frame with duct tape. The frustum
3 opening was sealed with a clear 0.63 cm thick acrylic panel edged with a closed cell foam
4 gasket. The air inside the open top chamber was mixed with four 0.5 m diameter propeller fans
5 each providing $82 \text{ m}^3 @ \text{m}^{-1}$ of air movement (Grainger Industrial Equipment, Lincolnshire, IL).

6

7 Inside the sealed open top chamber, a gas sampling array consisting of four Bev-a-line IV 6.4
8 mm OD plastic tubes (Ryan Herco Industrial Plastics, Burbank, CA) taped to a wire frame (four
9 arms at 90 deg arrayed in a horizontal plane) was installed at 2 m above ground level (top of
10 canopy within the open top chambers). This tube array was in turn connected to a 12V DC
11 diaphragm pump (TD-3LSA7, Brailsford & Co. Inc., Rye, New York). Sample gas was pumped
12 from the tube array at a flow rate of 0.5 l m^{-1} to a 2 l buffer volume, then to the sample side of
13 an infrared gas analyzer (IRGA, Li-Cor 6262, Li-Cor Inc., Lincoln, NE). The sample flow was
14 not returned into the sealed open top chamber, since the flow was quite small compared to the
15 chamber volume of 19.72 m^3 (Fig. 4.). The reference side of the analyzer was continuously
16 purged with air scrubbed through a column filled with Ascarite II (Thomas Scientific Inc.,
17 Swedesboro, NJ) and magnesium perchlorate.

18

19 Before sealing the chamber, a soil gas exchange system was installed in the chamber
20 (described below), and four propeller fans were placed into the chamber to insure a well mixed
21 system. All the seams along the acrylic panels were sealed using multiple lengths of duct tape.
22 Due to the difficult logistics of installing the frustum plug, and the need to keep air moving
23 through the chamber between measuring periods, the door was allowed to become the exit
24 pathway for air from the blower. This allowed "pre-installing" and sealing of the frustum plug to
25 the frustum. Immediately prior to beginning the measurement, the chamber fan motor was
26 turned off (along with the CO_2 injected into the fan air stream required for CO_2 enrichment), the
27 blower inlet sealed, and the door was then sealed in place using duct tape. Immediately after
28 the chamber was sealed the measurement started. A four minute time period was chosen
29 since it allowed a reasonable decline (or rise at night) of the CO_2 concentration with out
30 incurring more than a 5 deg C temperature increase (during the day). During the experiment
31 the sample gas was pumped from the array inside the chamber to the sample side of the IRGA,
32 the reference side of the analyzer was continuously purged with air scrubbed through a column

1 filled with Ascarite II and magnesium perchlorate (Fig. 4.). Air temperature and leaf temperature
2 inside the chamber were measured utilizing copper constantan thermocouples (36 gauge)
3 installed on the gas sampling array inside the chamber on a needle near the top of the canopy.
4 Data was collected utilizing a micro data logger (Campbell CR10, Campbell Scientific, Logan
5 Utah). At the end of each measurement period, the chamber door was immediately removed,
6 the blower inlet cleared, and the blower airflow and CO₂ flow restarted.

7

8 *Calculation Method*

9

10 Total net photosynthesis (A'_n) may be calculated as

11
$$A'_n = (C_b - C_f) V / \Delta t$$

12

13 where C_b is the initial concentration of CO₂, C_f is the final concentration of CO₂, V is the
14 volume of the cuvette, and Δt is the time between the start and stop of the measurement
15 (Field et al., 1989). Applying this measuring technique over the course of a 24 hour period
16 yields a diurnal course of water and carbon exchange (Fig. 5.). This technique was applied at
17 Placerville to at least two replicate chambers in each of the eight CO₂ vs. N treatments.
18 Accurate inter-comparison of the data is challenged by the ability to measure *in situ* leaf area of
19 the canopy. One method of avoiding this is to simply compare results on a unit ground area
20 basis (as shown in Fig. 5.). Comparison on a leaf area basis may be done by estimating LAI.
21 The diurnal whole chamber gas flux data shown in Fig. 5. illustrates our finding that the mid day
22 and daytime integrated rate of CO₂ uptake per unit ground area for the ambient +350 ppm
23 chambers is approximately 150% of the rate of uptake for the ambient chambers at each
24 nitrogen treatment (full data set not shown). The night-time whole chamber fluxes coupled with
25 the diurnal soil CO₂ efflux measurements indicate that return fluxes of carbon dioxide to the
26 atmosphere (via respiration) also increase at elevated CO₂

27

28

29 OPEN-FLOW GAS EXCHANGE MEASUREMENTS

30

31 The differential open flow gas exchange technique applied at the whole chamber scale was
32 used in Placerville beginning for the 1994 field season. The adoption of this experimental

1 approach was made for several reasons. First, the increase in leaf area and system biomass
2 that occurred during the previous year's growth increased system flux rates such that detection
3 with the differential open flow technique was possible. Second, the differential open flow gas
4 exchange technique avoids several of the key compromises involved with the closed system
5 approach, specifically rising leaf and air temperatures, decreasing (or increasing) CO₂
6 concentrations, and increasing H₂O partial pressures. The differential open flow approach is
7 also much less labor intensive, and is relatively insensitive to leaks that may be present in the
8 open top chamber (cuvette). However the differential open flow approach is technically much
9 more demanding, and cannot resolve low fluxes as well as the closed system approach. This
10 limitation is most apparent when attempting night time measurement of system fluxes, given
11 that plant and soil respiration are the two dominant processes. This is unfortunate, since far
12 less is known about CO₂ effects on system respiration (Amthor 1991, Ryan et al, 1994).

13

14 The differential open flow gas exchange technique has been well described in the literature
15 (Field et al., 1989; Bloom et al., 1980) and at the leaf level it is a readily accepted method for
16 the collection of mass flux rates. Application of this experimental method to the microcosm
17 scale has only been recently attempted (Leadley & Drake, 1993; Oechel et al., 1992; Daudet
18 and Claustres, 1995; Ham et al. 1995), and to date we are aware of only our attempt to utilized
19 this method on field grown forest stands dosed with elevated CO₂. Our objective for the 1994
20 field season at Placerville was to collect 24 hour records of net system CO₂ fluxes under similar
21 clear weather conditions with simultaneous above ground and soil surface measurements
22 taken. We consider that these data will allow insight into the potential for system carbon
23 storage because it quantifies the inputs, the net output, and indicates at least the relative
24 change in below ground carbon pools (when above ground and below ground efflux are
25 subtracted from the input).

26

27 *System description*

28

29 The overall system (Fig. 6) is schematically a very simple differential open flow gas exchange
30 system (see Ball, 1987; and Field et al., 1989 for a detailed description of leaf level systems).
31 The basic principle of a differential open flow gas exchange system is to sample an air stream
32 both before and after passing through a leaf cuvette, with the two sample gas flows going to the

1 reference and sample IRGA cells. The mass flow rate of air into the leaf cuvette is measured
 2 with a flow controller or flow meter. Application of this technique to an open top chamber
 3 requires that instead of measuring the air flow rate into the cuvette with a mass flow meter or
 4 controller, the air flow rate is found utilizing a trace gas calibration method (Field et al., 1989,
 5 Daudet and Claustres, 1995). This method is quite straight forward, and allows the calculation
 6 of mass flow rates by injecting a small volume of CO₂ at a known flow into a flow of air at a
 7 larger, unknown flow rate. By measuring the resulting increase in the CO₂ concentration in the
 8 mixed flow, the mixed flow rate may be calculated as follows:

$$9 u_a = (u_c / \Delta CO_2) - u_c \quad [mol \cdot s^{-1}]$$

10

11 Where u_a is the unknown air flow, u_c is the flow of injected CO₂, and ΔCO_2 is the differential
 12 from the IRGA. Alternatively, a pressure difference technique has been successfully applied to
 13 meet the same flow measuring need (Ham et al., 1993).

14

15 We found that utilization of the differential open flow gas exchange technique in the field, with
 16 the open top chamber as the cuvette, does require several modifications compared to systems
 17 designed to measure leaf level fluxes. Since ambient air is used as the source for air flow into
 18 the cuvette, it is critical that the "cleanest" possible source of air be utilized. Sampling of the
 19 air available at the fan inlet demonstrated that background CO₂ fluctuations of 10 to 20 :mol
 20 Amol⁻¹ could be expected, which induced unacceptable levels of noise into the signal. These
 21 fluctuations in the background concentration of CO₂ most likely are caused by polluted air
 22 exiting the 700 ppm treatment chambers (Davis et al., 1982) and were influencing the
 23 background levels measured at our empty test chamber, which is located down wind from the
 24 open top chamber array. We empirically found that relatively quiescent CO₂ background levels
 25 (" 5 to 10 :mol A mol⁻¹) could be obtained by drawing air into the fan through a 30.5 m long,
 26 61 cm diameter insulated flexible duct with the inlet positioned upwind to the open top chamber
 27 array, raised to 4 m above ground level. The addition of the inlet duct had the additional
 28 benefit of allowing sufficient mixing of CO₂ injected into the air stream flowing through the duct
 29 for the purposes of the flow calculation described above.

30

31 In order to maximize the ability to measure the signal generated by the pine trees, we chose to
 32 operate the chamber fans on low speed, which gives an average flow rate of 700-800 molAm⁻¹

1 (depending on the number of bends in the flexible duct). This in turn caused an associated
2 increase in the chamber temperature during the day of 7 deg. C (typically), which was in turn
3 mitigated by installing a coarse filter pad at the inlet and misting the filter with water. This
4 evaporatively cooled the incoming air stream, reducing the temperature gain to 2 deg C (on
5 average). We felt that this compromise was worthwhile, even though it causes an obvious
6 increase in chamber relative humidity, since the lower flow rate allows much finer resolution of
7 the CO₂ flux within the chamber.

8

9 Since any flow timing errors between the reference and sample sides of the system will induce
10 noise into the measurement due to the fluctuation in background CO₂ levels, the system
11 required mechanical integration of the sample and reference flows. This was accomplished by
12 flowing into 1.1 liter glass jars installed just upstream of the IRGA, continuously stirred by 12V
13 micro fans (Tandy Corp., Fort Worth TX) installed within the jar.

14

15 *Experimental method*

16

17 Application of this system in the field was driven by the requirement to measure system fluxes
18 over 24 different chambers, over a yearly time course, all within a very limited budget. In order
19 to insure adequate IRGA maintenance (zero and span drift correction), these functions were
20 automated within the system. The requirement of obtaining at least two measurements for a
21 chamber during any given hour, and the need to zero and span the single IRGA available to
22 this experimental apparatus dictated that only two chambers could be simultaneously
23 measured. At the top of each hour, a zero gas was switched to both sides of the IRGA, with
24 electronic zero capture utilizing a micro data logger (CR10, Campbell Scientific, Logan Utah)
25 after a 5 min. purge period. Next, a span gas was sent to the sample IRGA cell, with any drift
26 measured and corrected. The system would then check the air flow rate into each chamber,
27 utilizing an automated CO₂ injection method (as described above), finally, the differential
28 across each chamber was measured.

29

30 The open top chamber was prepared by first installing the soil gas exchange system (described
31 below), then installing four propeller fans to insure that the air sampled on the way out of the
32 open top chamber was well mixed. One fan was placed in each quadrant of the chamber. A

1 low density polypropylene plastic sheet with a 30 cm diameter hole in the center covered with a
2 "flapper valve" of the same material was taped to the opening in the frustum, to minimize any
3 incursions of ambient air (Leadley & Drake, 1993). An array of four intake tubes, connected in
4 parallel was installed just above the canopy, and the door panel was sealed in place with duct
5 tape. A 12V DC diaphragm pump (Brailsford & Co. Inc., Rye, New York) was used to draw the
6 sample from the sample array to the analyzer.

7

8

9 *Calculations*

10

11 Net photosynthesis (A_n) was calculated from the following relation:

12

$$13 A_n = u_a \cdot \Delta \text{CO}_2 / a$$

14

15 where u_a is the air flow entering the chamber, $\hat{\Delta} \text{CO}_2$ is the measured change in concentration
16 of CO_2 , across the chamber, and a is area, either leaf area, or ground area, depending on the
17 desired data presentation. Accounting for dilution of the CO_2 by evapotranspired water as
18 suggested by Ball (1987) was neglected in this case, since it would induce an error of well
19 under 1% and our ability to resolve flow contribute larger uncertainty to the measurements.

20

21 Transpiration, (E), was calculated similarly as:

22

$$23 E = u_a \cdot \Delta w / a$$

24

25 where w is the measured change in the mol fraction of water across the chamber. Again, the
26 increase in flow caused by the added water vapor in the chamber was very small compared to
27 the flow through the system, and was neglected.

28

29 *Sample time courses*

30

31 A typical time course for a high CO_2 high nitrogen chamber and an ambient CO_2 high nitrogen
32 chamber is shown in Figure 7. (Panel A and B) Characteristic in all the chamber
33 measurements in the noise seen in the data taken during the night, caused by fluctuating

1 background CO₂ concentrations. The carbon flux rates found for the high CO₂, high N
2 chambers are approximately double that measured for the ambient CO₂, high N chambers. By
3 graphing assimilation rates against photon flux density data, light curves may also be
4 constructed for whole chamber systems (Figure 7, panel C and D.)

5

6

7 SOIL GAS EXCHANGE SYSTEM

8

9

10 Gas exchange data necessary to allow partitioning of carbon between above and below ground
11 processes was collected concurrent with the above ground fluxes measured in the open top
12 chambers. Increasing, it is becoming apparent that much of the global change effect is found
13 below ground (Rogers and Runion, 1994), with implications to adjustments in nitrogen and
14 water cycling. While any soil gas exchange system that relies on closed volumes to capture
15 soil fluxes may be criticized for altering the surface from which the flux emanates, this
16 technology allowed at least some check on a large components of the night time carbon efflux
17 and was useful for comparisons between chambers. Measurements made with this system
18 that could be left in place through the course of several days of whole chamber measurements,
19 yielded flux values in the same range as have been reported from this experiment by Vose *et*
20 *al.* (1995) who also used fixed collecting vessels, as well as as measurements that we have
21 made with a Li-Cor 6200 system fitted with the soil respiration chamber. Spatial variability and
22 disturbance during chamber placement both contribute to uncertainty about soil fluxes so that
23 combinations of intensive and extensive measurements contribute to our confidence that our
24 estimates are contribute to the develop understanding of soil carbon budgets. Fluxes
25 measured by the fixed soil-cap system are labelled soil efflux in Figure 5.

26

27 *System description*

28

29 The soil gas exchange system utilized in this study was made up of six 15.25 cm diameter
30 PVC pipe caps, installed (three in each open top chamber) to a uniform depth into the soil
31 (allowing accurate calculation of system volume) with the interior space in the cap stirred with a
32 micro 12V DC micro fan (Tandy Corp). Each soil cap was provided with inlet and outlet tubing

1 (Bev-A-Line, Ryan Herco Industrial Plastics) attached to miniature diaphragm pumps
2 (Brailsford). When serially connected with the sample cell of an IRGA the system functions as
3 a closed chamber gas exchange system (as described for the closed chamber technique,
4 above). The gas sample lines were connected to solenoid valves, arranged so that for 55
5 minutes the cap inlet tube purged the cap and outlet tube with fresh air. When the 5 minute
6 measurement was begun, the valves switched the system back to a closed arraignment. This
7 was done so as to purge water vapor and CO₂ from the system, allowing relatively normal
8 conditions at the soil surface inside of the cap.

9

10

11 DISCUSSION

12

13 Utilization of open top chambers as cuvettes in which to measure whole system fluxes of
14 carbon and water has created an opportunity to better understand the results found by the
15 expensive, labor intensive elevated CO₂ studies underway at sites around the world. These
16 experiments must be undertaken with caution, however, given the difficulty of applying the
17 differential, open flow gas exchange technique at this large scale. The closed chamber
18 technique used at Placerville yields approximately the same percentage error as the open flow
19 technique, but allowed the measurement of fluxes that would have been challenging to capture
20 by any other method. The success of this closed method is dependent on the ability to
21 carefully seal the open top chamber, limiting the usefulness of the technique to those sites that
22 have installed rigidly glazed chambers, similar to the ones used at Placerville. Use of the
23 results obtained by this method are prejudiced by lack of steady state conditions during the
24 measurement period. Still, relative differences may be compared.

25

26 In order to successfully unravel the meaning of these integrated chamber measurements, we
27 believe that it is essential that , at a minimum, the below ground flux of CO₂ crossing the soil
28 boundary must be measured as well, given that soil respiration has been shown to be up to
29 40% of the system respiratory flux, and that this respiratory "loss" of carbon may be as high as
30 30 to 35% of that carbon fixed during the previous light period.. This information must be
31 obtained concurrent with the above ground measurements, which means that some sort of an
32 automated collection scheme be utilized. Calibration and maintenance of two separate gas

1 exchange systems in the field has proven to be a very expensive, and labor intensive
2 endeavor. The site chosen for the Ponderosa pine experiment does have the advantage of
3 offering long periods of sunny weather, thereby reducing the complexity of data interpretation.
4 Relating the data obtained to other leaf level measurements is dependent on carefully
5 estimating the leaf area contained within the chamber. We have utilized a Li-Cor LI-2000 leaf
6 area index meter for this purpose, and , time permitting, will attempt to capture digital images
7 with a wide angle lens in order to try to utilize another technique for obtaining this information.
8 We have found it useful to relate the chamber information on a ground area basis. While this
9 does not aid the task of interpreting the results on a leaf area basis, it does allow ready
10 exploration of relative differences between the chambers, and is readily scaled to large,
11 landscape based models.

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17 ACKNOWLEDGMENTS

18

19 This research was supported by the Electric Power Research Institute (RP3041-02) and the
20 United States Department of Energy Terrestrial Carbon Processes Program (DE-FG03-
21 95ER62013/A000). Technical assistance by Mistro James Courtney (Joaquimo Courtinii) of the
22 Metropolitan Opera Company, Olavi Kiirats, Sol Rogowski, Carol Johnson and Robin Petersen
23 is greatly appreciated. We thank Kevin Griffin for his comments on the manuscript.

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7 List of Figures

8

9 Fig. 1. Photograph of the open top chamber used in Placerville CA, constructed for the Forest
10 Response to CO₂ Program.

11

12 Fig. 2. Circuit diagram for the control circuit that switches fan speed between high and low
13 (day/night) and CO₂ injection rate between high and low flow (day/night). Relays 1 and 2 are
14 both mechanical, the photocell is solid state relay 1 reverses the logic of the photocell, and
15 allows low voltage distribution of the control circuit to the chambers distributed at the site.

16

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18

19 Fig. 4. System used for the closed chamber gas exchange method.

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21 Fig. 5. Diurnal course of water and carbon exchange measured utilizing the closed chamber
22 technique.

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24 Fig. 6. System used for the open chamber gas exchange method.

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26 Fig. 7. Diurnal course of water and carbon exchange measured utilizing the open chamber
27 technique.

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1 Figure 1.

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Chamber Picture

1 FIGURE 2.

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1 Figure 4.

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