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10. Canopy Gas Exchange in the Field: Closed Chambers

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I. INTRODUCTION

Intensive agriculture requires more efficient use of limited water resources. The increased importance of water use efficiency in agricultural production has prompted the need for new techniques to measure canopy photosynthetic carbon dioxide exchange rate (CER) and evapotranspiration rate (ET) in order to evaluate new soil and water management practices on water use and plant stress. The advent of remote sensing technology to study vegetative canopies by measuring optical, thermal, and microwave signatures provides potential for frequent characterization of plant performance in the field. This new technology has increased the need to provide ground truth data for calibration and validation of satellite data on unit land area basis. Current instrumentation is inadequate to meet this need. The philosophy for measuring ET and canopy CER on a unit land area basis evolves from the need to predict economic yield on a unit land area basis. Measurement of the physical and physiological characteristics of plants and the biophysical processes at the earth's surface, such as photosynthesis and evapotranspiration, can facilitate the interpretation of remotely sensed data of surface conditions. This work briefly describes the development and performance of a closed transient portable chamber for rapid field measurements of canopy photosynthesis and evapotranspiration.

II. THEORY

Information on the physical and theoretical concepts and the development of equations to calculate carbon dioxide exchange rate (CER) and evapotranspiration rate (ET) are presented in Sesták *et al.* (1971), a key reference in the theoretical development and understanding of techniques for measuring CER and ET. Further details on other aspects of calibration and methods of calculation are presented by Peters *et al.* (1974), Reicosky *et al.* (1990), McPherson *et al.* (1983), Meyer *et al.* (1987), and Lake (1972). This chapter describes a closed chamber with no control over water vapor increase or CO_2 decrease and the internal microclimate. Other types of large canopy chambers are described by Peters *et al.* (1974), Christy and Porter (1982), Musgrave and Moss (1961), Meyer *et al.* (1987), Daley *et al.* (1984), Harmsen *et al.* (1982), and Garrity *et al.* (1984).

The principle for the closed-chamber technique was first described by Lange (1962). The "Klapp–Küvette" was the first practical chamber of this type. It was a tiltable trap-type chamber for single leaves, used in combination with an infrared gas analyzer and a sequencing valve. The chamber closed and the air was circulated through the infrared gas analyzer for CO_2 analysis. Most of the same principles apply equally well to either small single leaf chambers or to large canopy chambers. The objective is to move the chamber over the plant canopy, lower the chamber, and rapidly collect the data to determine the rate of CO_2 decrease and water vapor increase and then raise the chamber and move to the next plot. Canopy CER and ET are calculated from the gas exchange rates on a mass basis, the chamber volume and soil area. In theory, making the measurements using a transient closed chamber technique assumes the short duration of the chamber over the plants should have only a minimal effect on CER and ET. However, it is difficult to determine the magnitude of the chamber effect on stomatal response even for the short term. Clearly the presence of the chamber will have some effect on the plants; however, rapid measurements will minimize this effect and result in only a minimal impact on the calculated CER and ET.

The portable chamber described here was first reported by Reicosky and Peters (1977). The portable chamber, which was constructed of clear plastic material mounted over a metal frame, was mounted on the front end of a farm tractor. Construction details of the portable chamber that permits measurements over 76 cm and 102 cm row spacings for small corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.) were provided by Reicosky and Peters (1977) and later modified to go over 3 m tall corn. The current version of the chamber contains four fans for complete mixing of the air and is mounted on a hydraulic forklift mechanism attached to the front end loader of a medium-sized (45 kW) farm tractor. The tractor transports the chamber and recording equipment from plot to plot, along with the portable generator that powers equipment in remote field locations.

The tractor with the portable chamber in the "up" position is maneuvered until the chamber reference points align with the reference stakes and then the chamber is lowered. Initially, data were collected at 2 second intervals with the chamber over the plants for 80 seconds with the fans continuously running and then the chamber was lifted. Currently the chamber is over the plants for only 60 seconds. While the chamber is moving to the next location, the rates of CER and ET are calculated and printed out for immediate analysis and decision-making and the raw and calculated data are stored on tape for further processing on the main computer. For each measurement, the time the chamber contacts the soil, the plot identification, the solar radiation, photosynthetically active radiation, air temperature, wet bulb temperature, and infrared thermometer output are recorded.

III. CALIBRATION

The initial calibration described by Reicosky and Peters (1977) utilized a unique hydroponic system to accurately measure water uptake by a soybean canopy in the field and compared that to the transpiration measured with the portable chamber. The linear relationship between the transpiration measured with the chamber and the uptake rate measured by the hydroponic system with the slope near unity (0.981) and a reasonably good R^2 (0.980) indicated that the transpiration rate was measured accurately by the chamber. The soil surface during these measurements was covered with plastic film to minimize the effect of soil evaporation contributing to the water vapor increase in the chamber.

A second calibration was done by comparing alfalfa ET measured with a precision weighing lysimeter with that measured by the portable chamber in close (10 m) proximity when the alfalfa was approximately 0.70 m tall (Reicosky *et al.*, 1983). Chamber measurements of ET were made at 10 minute intervals throughout the day and averaged each hour. These chamber measurements were compared with hourly measurements of a precision weighing lysimeter. Ground cover was complete and full canopy had developed with no visible difference between the canopy stature in the lysimeter and in the chamber measurement area. The lysimeter and surrounding area had been irrigated with 50 mm of water the preceding day.

The diurnal patterns of ET from the lysimeter and the portable chamber showed reasonable agreement (Reicosky *et al.*, 1983). Both ET measured with the weighing lysimeter and the portable chamber went through the expected diurnal patterns when compared on an hourly basis and were related to the solar radiation and the vapor pressure deficit. The maximum ET for the lysimeter was 0.85 mm hr^{-1} and for the portable chamber was 0.80 mm hr^{-1}. The relationship between the hourly ET measured by the lysimeter and the portable chamber was nearly linear. On an hourly basis the chamber ET was as much as 0.16 mm hr^{-1} lower than the lysimeter ET at 1100 hours and as much as 0.09 mm hr^{-1} higher than the lysimeter ET at 1800 hours with much better agreement during the rest of the day. Although the maximum difference between the lysimeter-measured ET and the chamber-measured ET for 1 day was 19%, the difference at other times was considerably less, suggesting caution when drawing conclusions from such a limited data set. Caution is needed in this comparison due to the relatively "short time" required for the chamber measurement and the relatively "long time" for a measurable weight loss in the lysimeter system. Care must be exercised to integrate chamber measurements to be comparable with the longer integration period required by the lysimeter. However, the reasonable agreement with potential ET calculated from microclimate data as an indicator of evaporative demand suggests that the chamber may yield reasonable results on other days with climatic extremes (Reicosky *et al.* 1983). Daytime cumulative ET values between 0500 and 2100 hours were 7.97 and 7.71 mm for the lysimeter and the chamber, respectively. The reasonable agreement between the chamber and the lysimeter throughout the day and the cumulative daytime ET suggest that the chamber may be satisfactory for measurements of crop water use on field plots.

Peters *et al.* (1974) calibrated CO_2 flux by injecting a known mass flow rate of CO_2 through two rows of hypodermic needles inserted into the canopy area within the chamber. The mass flow rate of CO_2 was controlled and measured by a commercial flow meter. During the period of injection, the chamber was placed over the calibration area and the rate of change of CO_2 was recorded, using a differential CO_2 analyzer with the full-scale range of 100 μmol CO_2 mol^{-1}. The volume of the chamber was calculated from the internal dimensions of the chamber that included the volume of the fans and the pump. From the CO_2 injection calibration, the chamber volume was calculated independently, using the effective ground area covered by the chamber and the density of CO_2 injected. From the calibration, a change of 1 μmol mol^{-1} in 4 minutes was equivalent to the photosynthetic or respiration rate of 0.0371 g CO_2 m^{-2} hr^{-1}. A photosynthetic rate of 5 g CO_2 m^{-2} hr^{-1} would require a 33 μmol mol^{-1} change in CO_2 concentration per minute. Similar calibration was done by Christy and Porter (1982).

Recent improvements in instrument sensitivity and modifications of the closed-chamber technique have been described by Reicosky *et al.* (1990). A BINOS-Model 4b.2 (Leybold Hereaus) Infrared Gas Analyzer (IRGA) was used to measure CO_2 and H_2O concentration in the differential mode (range of ±50 μmol mol^{-1} CO_2 and ±10,000 μmol mol^{-1} H_2O). The gas sample was pumped to the IRGA through a 6.35 mm ID polypropylene tube at 34 L min^{-1}. A portion of the gas was subsampled at 2.5 L min^{-1} for analysis. Another portion of the sample was drawn off at 2.5 L min^{-1} to a 65 L reference tank to isolate and buffer fluctuations in the reference gas. The CO_2 and H_2O vapor concentrations in ambient air were used to allow the reference gases to follow diurnal changes in concentration that were as large as 30 and 5000 μmol mol^{-1} for CO_2 and H_2O, respectively. During the 60 second data collection period, analog output from the two channels of the IRGA, along with other microclimate data and the closure switch, was recorded every 2 seconds via a computer-controlled data acquisition system, as described earlier. The computer was mounted on the fender of the tractor and the rest of the equipment was contained in an instrument shelter mounted on the back of the tractor. The IRGA output, air temperature, and solar irradiance were also recorded on a strip chart to provide immediate visual evidence of any erratic behavior in the change in CO_2 and H_2O vapor concentration. The strip chart recorder was critical for immediate identification of spurious results that may necessitate a repeat measurement.

Within the 60 second data collection period, a 30 second calculation window was initially selected to calculate CER and ET. The calculation window normally began 16 seconds after chamber closure to ensure adequate lag time for the gas sample to reach the IRGA. Several other calculation windows were tried; but experience showed 15 values of the CO_2 concentrations, corresponding to a 30 second calculation window, were best to routinely calculate the rate using the concentration regression method (Reicosky *et al.*, 1990). This method represented a practical compromise between the minimum number of data points required to

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give calculated CER and ET rates with acceptable variability (r^2 consistently 0.98 or higher) and a sufficiently small calculation window to minimize the effect of the altered environment within the chamber.

The gas lag, which is the time required to bring the gas sample from the chamber to the analyzer, was characterized by the time required for the BINOS to respond to a pulse of CO_2 introduced in the chamber. However, with low external wind velocities and in very dense canopies of soybean and corn, where the leaf area indexes ranged from 3 to 6, an additional canopy mixing lag is required. The high leaf area density decreases the amount of mixing and affects the CO_2 and water vapor profiles. With an actively growing canopy, there is depletion of CO_2 within the canopy of the order of 10 to 15 μmol mol^{-1} and an increase in water vapor such that the air within the plant canopy is different from the air above the canopy and in the chamber prior to lowering. These large differences in CO_2 and water vapor concentration need to be uniformly mixed prior to getting a uniform linear rate of CO_2 drawdown and water vapor increase using the closed-chamber technique. With the large chamber over dense canopies of corn and soybean, an additional 10 seconds were required for the canopy mixing lag. The density of the foliage in the chamber and the CO_2 depletion and water vapor buildup in the canopy under low wind speeds require this additional mixing to get a representative sample and a linear rate of change.

Using the sensitive differential IRGA for both water vapor and CO_2 and an automatic data acquisition system, operating off a portable generator required the evaluation of potential electrical errors (Reicosky *et al.*, 1990). The magnitude of the error associated with the method of measurement, the calculation, and the sensitivity of the equipment was determined using a 2 second sampling interval and a total data collection period of 5 minutes. The total error associated with the fluctuation in the apparent gas concentration as a result of using the "floating" reference gas for water vapor and CO_2 was evaluated in addition to those errors possibly caused by the electrical noise associated with the portable generator. With the large chamber (8.15 m^3) in the up position and using normal gas flow procedures, the fluctuations in the incrementally calculated CER, using the concentration regression method and a 30 second calculation window, were relatively large due to fluctuations in the sample gas caused by people and vehicles in the area. This was confirmed by operating the chamber in the down position over stainless steel sheets sealed to prevent CO_2 from soil respiration and ambient gas outside the chamber entering the chamber.

The rates of change of the differential CO_2 concentration as a function of time with the chamber over stainless steel sheets were given in Reicosky *et al.* (1990). The differential concentration ranged from 15–20 μmol mol^{-1} on the four different runs, reflecting a concentration difference between the reference and ambient, resulting from the time lag of the reference gas. This difference was constant within a given data collection period. The incrementally calculated CER within any one of the 30-second windows of the data sets for the 5 minute period showed an isolated extreme of 0.5 g CO_2 m^{-2} hr^{-1} and for three of the four data sets was less than 0.2 g CO_2 m^{-2} hr^{-1}, suggesting little variation in the differential CO_2 concentration as a function of time with the chamber in the down position.

The incrementally calculated CER includes the multiplication factor for the chamber volume:area ratio of 3.05 that tends to inflate the magnitude. Theoretically, the calculated CER should have been zero. The mean CER values for each run were near zero, and the standard deviation within a data set ranged from 0.062 to 0.153 g $CO_2\,m^{-2}\,hr^{-1}$. The variations in CER from the range of standard deviation, using the concentration regression method of calculation, suggest a nominal range for the CER fluctuations from -0.2 to $+0.2$ g $CO_2\,m^{-2}\,hr^{-1}$ for the large chamber. These preliminary results provide estimates of the system accuracy and give some confidence that the errors using a portable generator as a power source were not significant, provided extraneous sources of CO_2 are not a problem. The small measurement error when the chamber was used in the "down" position suggested use of a floating reference gas with the IRGA in the differential mode for the measurement and calculations of CER was reasonable.

The error associated with small CO_2 leaks using the closed chamber technique can be corrected for using the calibrations technique of Peters *et al.*, (1974). However, the error is considered small relative to other errors associated with the method of measurement. Gaseous diffusion through small holes with a low concentration gradient would suggest a small error. The large chamber volume, strategic fan placement and mixing patterns, the initial zero concentration gradient, the absence of a pressure differential and the dynamic nature of the measurement make small leaks a minor concern. Techniques for correcting leakage errors where the concentration difference in and out of a semi-closed chamber is large have been presented by Acock and Acock (1989). The potential errors of H_2O adsorption on the chamber walls and in the tubing have not been fully evaluated.

IV. EXAMPLE RESULTS

The effects of dynamic environmental variables, particularly solar radiation, on CER and ET require microclimate data be collected in association with the chamber measurements. An example showing the diurnal pattern of ET measured with a psychrometer in the chamber at three different soybean row spacings is summarized in Figure 1 (Reicosky, 1985). Measurements were made on different treatments at approximately 5-minute intervals, starting shortly after sunrise and continuing until late in the afternoon. The individual data points are plotted for each of the measurements and a line drawn through the data points, using a 1-2-3-2-1 weighted running average to smooth the diurnal trends. While there was a consistent difference between irrigated and nonirrigated treatments, the row spacing effect suggested a larger difference in ET between irrigated and nonirrigated soybean for the 0.15 m row spacing than for the wider row spacings. These data were collected shortly after the soybean canopy had reached maximum leaf area index for all three row spacings. The larger difference between irrigated and nonirrigated 0.15 m row spacing suggests the narrow row spacing extracted

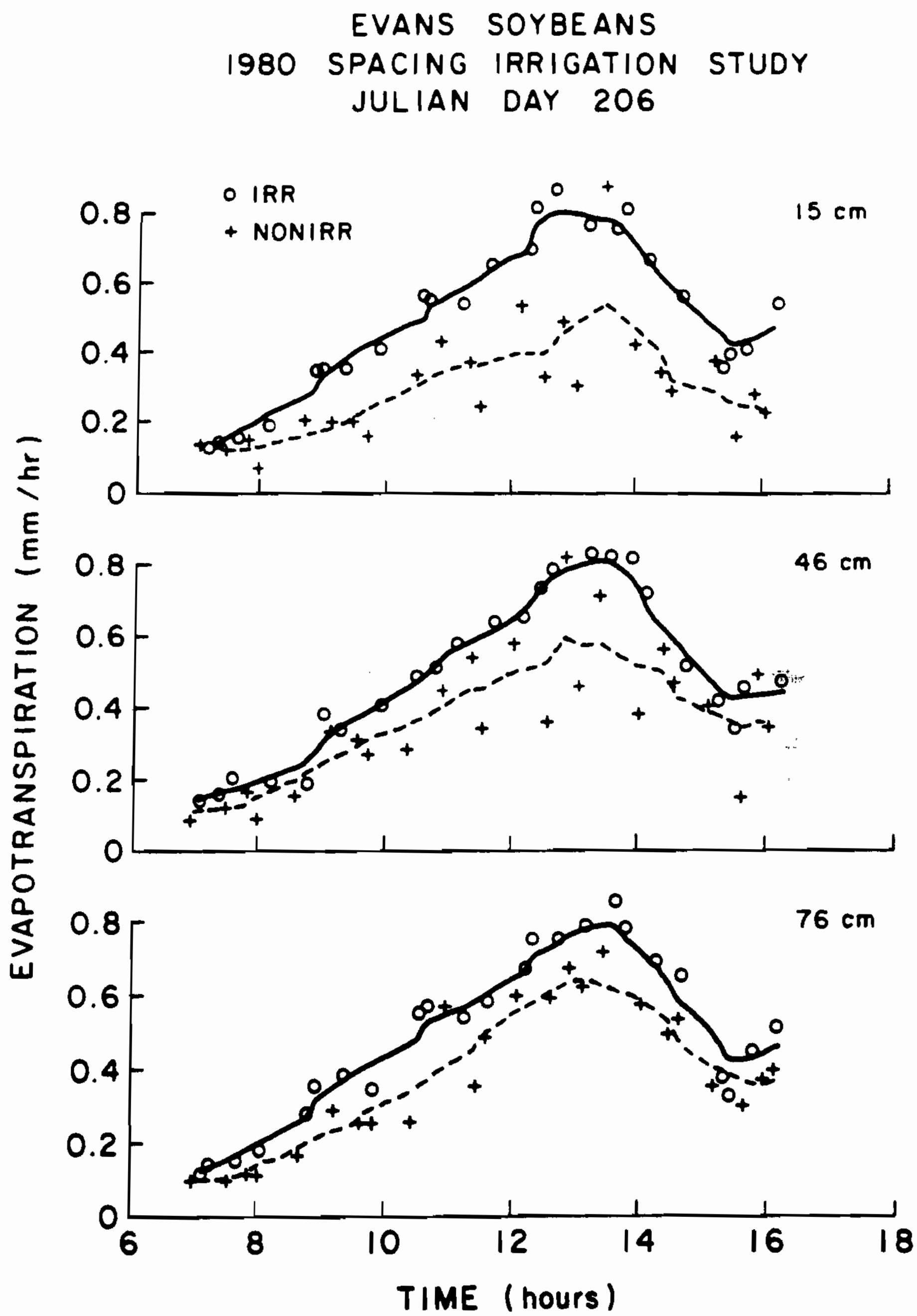

FIGURE 1 Diurnal trends in soybean evapotranspiration affected by row spacing and irrigation (*from* Reicosky, 1985).

soil water earlier and resulted in more stress. Similar results were obtained in a more comprehensive study by Reicosky *et al.* (1982).

An example of canopy photosynthesis and ET data for corn is summarized in Figure 2 (Reicosky, 1985). These data were collected on a farmer's irrigated field near O'Neill, Nebraska, on 5 August 1981 to determine the effect of plant density on canopy photosynthesis. Corn was planted, using conventional techniques, with two areas thinned when the corn was about 0.3 m tall to give low, medium, and high populations. The CER and ET measurements were made one day after 50 mm of rain fell which was also 20 days after anthesis, when the plants were 3.5 m tall.

The data in Figure 2 show the effect of photosynthetically active radiation on CER, and the potential magnitude of CER for generally clear days and high population. The drastic effect of isolated clouds on CER points to the potential problems using one point in time measurements to infer treatment effects. The maximum recorded value for CER was 9.6 g $CO_2\,m^{-2}\,hr^{-1}$ not adjusted to account for the CO_2 released from soil respiration. Independent measurements over an adjacent undisturbed, bare, weed-free soil at the end of the corn rows showed a soil respiration rate of 2.0 g $CO_2\,m^{-2}\,hr^{-1}$. There were no metabolically active roots below the soil surface. While this soil respiration was obtained from a moist soil surface, the magnitude of CER in these conditions illustrates high rates during the ear filling period (see Figure 2). Plant density had a drastic effect on the canopy photosynthesis but only a limited effect on evapotranspiration due to the previous rainfall and the wet soil surface (Reicosky, 1985). Examples of full season net canopy photosynthesis of soybean at four different populations are given in Christy and Porter (1982) and for corn in Pearson *et al.* (1984) and Christy *et al.* (1986).

The sensitivity of the chamber was evaluated by making measurements of soil evaporation and respiration on bare plots with no actively growing vegetative material on an extremely dry soil during the drought of 1988 (Reicosky, 1990). Two plots were identified; one with a slight weed problem was raked to a shallow depth (2 cm) for weed control that resulted in a fine mulch on the soil surface. A second area was weed-free but had large cracks (about 1 cm wide) from drying of the expanding type clay in this soil. The chamber measurements several days later showed different evaporation and respiration rates on the "cracked" soil and the "mulched" soil in Table 1. Both the evaporation and respiration rates were very low as expected with the evaporation rate from the "cracked" soil consistently larger than that from the "mulched" soil. The difference in soil evaporation was also reflected in the change in surface gravimetric water content where the cracked soil showed a more rapid decrease as the drought progressed. The practical implications of the small differences in soil evaporation and respiration may not warrant management practices to conserve the small amount of water on an absolute basis. However, the results in Table 1 do illustrate the sensitivity and the repeatability of the chamber with a sensitive IRGA at low evaporation and respiration rates. It is noteworthy that the respiration rates approximate the calculated values of CER (± 0.2 g $CO_2\,m^{-2}\,hr^{-1}$) measured over stainless steel plates described earlier (Reicosky *et al.*, 1990).

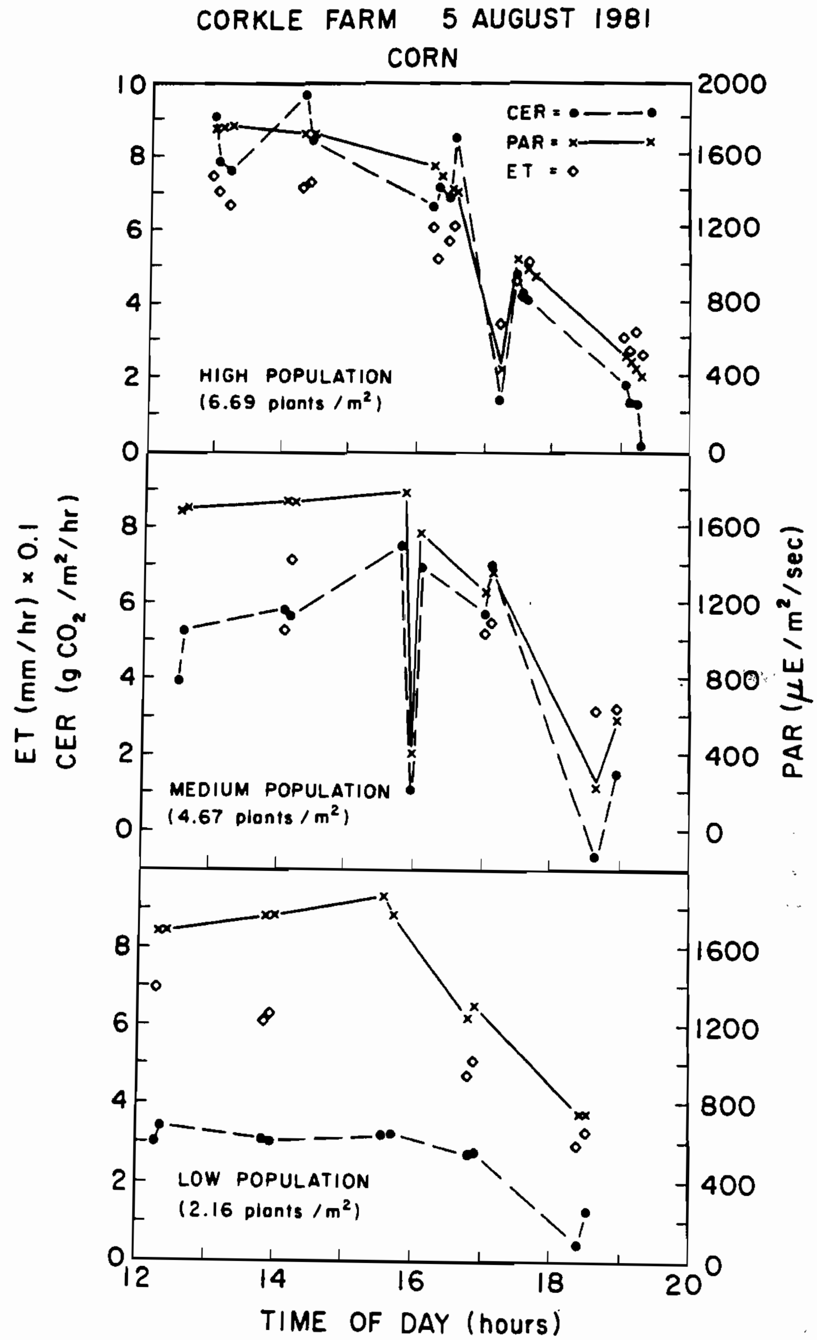

FIGURE 2 Corn canopy photosynthesis (CER) and evapotranspiration (ET) as affected by plant population and cloud cover (*from* Reicosky, 1985).

TABLE 1
Summary of midday soil evaporation and respiration on the "raked" and "cracked" soil on 12 May 1988.

Sample	Soil Evaporation ($mm\ hr^{-1}$)		Soil Respiration ($g\ m^{-2}\ hr^{-1}$)	
	"Raked"	"Cracked"	"Raked"	"Cracked"
1	0.089	0.138	−0.193	−0.062
2	.074	.137	− .205	− .149
3	.072	.109	− .283	− .072
4	.066	.102	− .235	− .002
5	.067	.111	− .287	− .307
Mean	.074	.119	− .241	− .118
Std. Dev.	.009	.017	.043	.118

V. COMMERCIAL PRODUCTS

The following list of components and instruments in Table 2 are currently used in the portable chamber system. These are provided as a source of information and starting point for others recognizing that equipment by other manufacturers may be suitable. The technology is changing rapidly and some components of this system have been modified on a continuing basis as funds become available. More economical data acquisition equipment is available now than was available 5 or 6 years ago.

The tractor and the vertical hydraulic lift used in the portable chamber are not unique but do need to be of sufficient size and sturdy enough for the chamber to be lifted over the crop of interest (at least 3 m for corn). The tractor needs an auxiliary hydraulic pump to operate the vertical mast and needs to be heavy enough to be stable (preferably 4 wheels with wide front wheels, not tricycle-type) when the large chamber is in the "up" position at high wind velocities. Power steering is essential for precise placement and maneuvering the chamber over the plots. The exhaust from the generator and the tractor need to be exited as high as possible to minimize the CO_2 that enters the chamber. This often requires working with the chamber into the wind so that the exhaust is blown away from the input of the gas sampling tube. Low wind conditions require carefully moving the chamber so that the front of the chamber is always moving into the wind.

The BINOS infrared gas analyzer was selected because it has a two-channel system for CO_2 and H_2O that can operate in the differential mode or in the absolute mode with its own internal pumps, flow meters, and filters. The BINOS has a fast time response (1.8 seconds) with a small cell volume (90 cc) and a high flow rate ($2.7\ L\ min^{-1}$) that contribute to the rapid overall response. It has an optical filter to minimize the effects of water vapor on CO_2 linear analog output (0–1 volt) with 150% over-ranging, can operate off 110 volt AC or 12 volt DC, and is relatively insensitive to vibration. However, the use of the BINOS under the adverse field environment with vibration caused by the tractor and generator required additional packing with polyurethane foam to minimize the vibration effects. We used the BINOS in the differential mode, using a floating reference

TABLE 2
Summary of major equipment suppliers and approximate price purchased from 1980 to 1986. Names of products are provided for the benefit of the reader and do not imply endorsement or preferential treatment by the USDA or University of Minnesota.

FUNCTION	EQUIPMENT	SUPPLIER OR MFGR	LIST PRICE
Measure CO_2 and H_2O concentration	BINOS Infrared Gas Analyzer (Model 4.2b)	Inficon Leybold-Heraeus Inc. 6500 Fly Road East Syracuse, NY 13057	$16,000
Computation, control and immediate printout	HP 85 Calculator (Model 85b)	Hewlett Packard 2025 West Larpenteur St. Paul, MN 55113 612-644-1100	5,250
Data Collection	HP Data Acquisition System (Model 3054A)	Hewlett Packard 2025 West Larpenteur St. Paul, MN 55113 612-644-1100	6,720
Hard Copy output of data for immediate analysis	4-pen Strip-chart Recorder (Model L-2041)	Linseis P.O. Box 666 Princeton Jct., NJ 08550 1-800-732-6733	4,916
Measure air and wet bulb temperature	2-Thermistors and Electronics (Models 705 and 742A-1)	Yellow Springs Inst. Co. P.O. Box 279 Yellow Springs, OH 45387 513-767-7241 (or general catalog)	262 est.
Transport chamber	Farm Tractor (1974) (Model 5600-LA 215M) 45 kW, 3362 kg	Ford Tractor Operations Ford Motor Company 3000-T Schaefer Road P.O. Box 6011-T Dearborn, MI 48121 1-800-722-5787	15,000 est.
Lift and tilt of chamber	Front-end Loader (Model 735 Industrial)	Ford Tractor Operations Ford Motor Company 3000-T Schaefer Road P.O. Box 6011-T Dearborn, MI 48121 1-800-722-5787	4,000 est.
Vertical lift of chamber	Vertical Hydraulic Mast (Model-used)	Mott Company 1720 New Brighton Blvd. Minneapolis, MN 55413 612-782-1400	930
Portable A/C power	Generator (6500 watts) (Model 6.5 PM-3E/20000)	Onan 1400 73rd Avenue N.E. Minneapolis, MN 55432 612-574-5000	1,290
Mix air in chamber	4 Shaded Pole Blowers (each 13.16 m^3 min^{-1}, 115 Volts) Stock # 4C448	W. W. Grainger Inc. Distribution Group 2450 Anapolis Lane, N. Plymouth, MN 55441 612-559-0405	38 ea

because of the dynamic nature of the ambient CO_2 and water vapor concentrations throughout the day. Experience and loss of one year's data suggest caution in the use of the proper air filters within the system. The distributor supplied the instrument with cellulose filters that worked properly for CO_2 but not for water vapor. Either Teflon or stainless steel filters are needed when both water vapor and CO_2 are analyzed simultaneously.

The computer-controlled data acquisition system incorporated a HP-85B microcomputer, chosen because of a built-in tape drive, a thermoprinter, limited graphics capability, and was easily programmed in BASIC, in a relatively compact unit. The data acquisition system had the necessary sampling rate and precision required to read low level signals (e.g., thermocouples) in subsequent measurements. The vigorous vibration from the tractor and the dusty conditions made the HP-85B tape drive critical for data and program storage. Other computers with disk drives probably would not survive the adverse working conditions. However, the advent of bubble memory or other computers with specially designed disk drives (e.g., military or robust industrial specifications) may make the requirement for a tape drive obsolete.

The Linseis 4-pen recorder was selected for immediate assessment of the rates because it had a wide range of chart speeds, multiple ranges for voltage signals, and built-in over-ranging capabilities. An additional event marker and a remote control option for starting the chart drive through the data acquisition system was convenient. The recorder could handle either chart rolls or fan-fold paper, with fan-fold most convenient for quickly reviewing traces. The pens were disposable and easily changed in the dry field conditions.

The clear plastic material covering the chamber the last few years has been Lexan. Plexiglass and Mylar have been used with little difference noted in the performance of the plants. Lexan is the preferred material because it is more durable and does not tend to scratch as easily as the Plexiglass and is easier to change than flexible Mylar. Peters *et al.* (1974) continue to use Mylar while Harmsen *et al.* (1982) have used Propofilm C/100. Jarvis (1970) discusses the thermal radiation balance of leaves and presents the transmittance of various materials commonly used on assimilation chambers.

The YSI Model 705 thermistors (Part #44202) for air and wet bulb temperatures were selected because of their linear output over -5 to 45°C range (-50 to $+450$ mv) and their rapid time response (0.6 sec). Caution is required on how the wet bulb is established and the thickness of the wick material used to cover the wet bulb. Experience showed the thickness of a normal cotton wick had a thick film of water that required additional time to change temperature, causing the wet bulb temperature change to lag behind the dry bulb temperature change. A very thin layer of cotton cheesecloth or alternately a single layer of Kleenex tissue to maintain the wet bulb where the water was supplied under gravity from a ventilated hypodermic syringe was satisfactory.

Photosynthetically active radiation and/or solar radiation measurements during each chamber measurement are essential to characterize cloud effects in humid areas and also can be used to relate CER to light intensity. These sensors identify changes in solar radiation during a measurement and aid in analyzing and interpreting the data.

Soil respiration and evaporation can be separated from the plant components in row crops using barriers. A bifold barrier lined around the perimeter with foam was pressed between the rows to cover the soil in corn and soybean to enable measurements with the barriers to eliminate soil respiration and evaporation. However, this requires two separate measurements to get at soil respiration and evaporation by difference. Covering the soil in solid seeded crops becomes more difficult; however, a gravel mulch or polystyrene beads as a mulch can be used to minimize the exchange from the soil surface in small grains and solid seeded soybean.

VI. LIMITATIONS

Conceptually, the portable chamber offers advantages of making field measurements in place with spatial averaging and large numbers of plants included in the measurement. The current version represents a practical compromise of some of the theoretical limitations and latest technology to make measurements as rapidly as possible. Measurements on a land area basis are more easily related to satellite data and remote sensing instruments that measure plant parameters on a land area basis. *Direct measurement of CER and ET on unit land area basis has the decided advantage of not having to extrapolate single leaf or single plant data to canopy level data.* Some of the advantages and limitations of the portable chamber are summarized in Table 3. Of prime importance, the climate is not controlled within the chamber and the chamber measurement represents only one point in time and space. Turbulent mixing may be a problem and needs to be carefully considered (Jarvis, 1970). In certain situations where soil evaporation and soil respiration need to be accounted for, additional measurements may be required.

The modification of the microclimate within the chamber may be a problem, but recent measurements of leaf temperature in and out of the chamber with infrared thermometers and thermocouples suggest that changes in leaf temperature have only a limited effect on CER (Reicosky and Wagner, unpublished). More important is the rapid buildup of water vapor, as noted by Daley *et al.* (1984), within the chamber that appears to marginally affect ET. The results are still being analyzed; however, the water vapor buildup appears to be only associated with high humidity and relatively high ET. Repeat measurements within 3 to 5 min with the chamber over stressed and nonstressed corn have not shown any effect of the chamber on CER and ET; however, repeat measurements over stressed soybean showed significant decreases in CER and ET from frequent measurements. As a result of these observations, the field plots are sampled sequentially so no measurements are repeated on the same soybean plot for at least 30 min. These observations will require further research to fully characterize their significance in the measurement of CER and ET. The size of the portable chamber and the expense of the equipment are limitations but are required for making accurate field measurements with the necessary precision and speed to provide accurate data for satellite calibration and making intelligent management decisions.

TABLE 3

List of advantages and limitations of transient portable chamber for measurements of canopy photosynthesis and evapotranspiration.

	Advantages		*Limitations*
a.	Flexibility enables CER and ET measurements in remote field plots.	a.	Brief unnatural environment that disturbs spatial and aerodynamic characteristics inside chamber for absolute measurements.
b.	Measures entire plant canopy and expresses activity on unit land area basis.	b.	Represent "instantaneous" value as one point in space and time for dynamic data.
c.	Simple operation and rapid measurement (60 sec.).	c.	Requires separate measurements of soil respiration and evaporation if it is desired to separate the soil and plant components.
d.	Evaluate several genotype and soil and plant management practices not practical in lysimeters.	d.	Intermittent clouds in humid environments can be a problem in interpreting results.
e.	Virtually nondestructive and spatially averages entire canopy and large number of plants.	e.	Requires large and expensive equipment, large operating area, and critical directions operating into the wind.
f.	Adaptable to small plots where micrometeorological techniques and fetch requirements for Bowen Ratio and Eddy Correlation techniques are not readily adapted.	f.	Subject to the vagaries and dynamics of the micro-climate such as dew formation.
g.	Can be used to evaluate variability for model validation.	g.	Chamber does some damage around the perimeter with repeated measurements.
h.	Requires only one operator once plots are established.	h.	Not able to do frequent repeated measurements on soybean.
i.	Plants under natural environment at all times other than the measurement time.	i.	Presently used for daytime values only.
		j.	Rapidly changing leaf temperature, humidity, and CO_2 concentration may affect species stomatal sensitivity differently.

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