A PORTABLE CHAMBER FOR EVAPOTRANSPIRATION MEASUREMENTS AND IRRIGATION SCHEDULING

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Abstract

Improved water management to increase water use efficiency requires development of research tools that provide accurate measurements of evapotranspiration (ET). The objective of this work is to describe a portable chamber for measuring ET in the field and to show its utility for developing and evaluating irrigation scheduling criteria. The chamber is placed over the canopy for 60 seconds and the rate of water vapor increase measured with an infrared gas analyzer. Midday leaf water potential and canopy air temperature collected on corn and soybean during the 1988 growing season were related to ET. Days selected for detailed analysis were during maximum leaf area index around anthesis, cloud-free, and at least two days from rainfall or irrigation to minimize soil evaporation and respiration contributions to the net gas exchange. The chamber was accurate over a wide range of evaporation rates from a low of 0.04 to a high of 1.1 mm hr^{-1}. Results from this field study showed ET related to leaf water potential, with both decreasing as soil water stress became severe. Air temperature within the canopy of stressed corn and soybean increased progressively during periods of high evaporative demand as soil water deficit increased. Within-canopy air temperatures can increase as much as 4 to 6 °C while ET decreased to about 20% of ET on irrigated plots. High in-canopy air temperatures were associated with leaf water potentials that ranged from -1.6 to -3.0 MPa for both corn and soybean. The relationship between ET and leaf water potential and in-canopy air temperature during severe soil water deficits suggest ET measured by the chamber can be used to develop and evaluate simple irrigation scheduling techniques.

1. Introduction

Proper evaluation of water resources and more scientific management of water requires the development of improved irrigation scheduling methods and satisfactory measures of crop water use that will result in increased water use efficiency. Irrigation scheduling generally reduces to two questions: when to irrigate and how much water to apply. These are the primary irrigation management decisions that need to be made and can have the most effect on crop yield and efficient water use. Scheduling techniques range from simple soil water monitoring to using sophisticated computer programs to predict crop water use. Both methods of predicting crop water use are based on meteorological measurements and only in a limited number of situations has actual ET been incorporated. Various combinations of irrigation scheduling methods have been used throughout irrigated areas. Unfortunately, not all relations between climate and plants and soil are transferrable from one geographic location to another. As a result, coefficients used to describe these relationships must be reevaluated for each specific region that scheduling is attempted. The portable chamber for quantifying ET under field conditions can be a valuable research tool for developing selected coefficients for irrigation scheduling programs. Tools frequently used in evaluation of evapotranspiration (ET) are the weighing lysimeter and the assimilation chamber reviewed by Tanner (1967).

Portable chambers can provide direct measurements of ET that can be used to evaluate irrigation scheduling techniques. Peters et al. (1974) describe an automated system that measures canopy photosynthesis (carbon dioxide exchange rate, CER) and ET simultaneously. Reicosky and Peters (1977) have described a portable chamber for the rapid measurement of ET on field plots. Results from other studies have been presented by Reicosky (1981, 1984, 1985). While there is still some question about the validity of chamber measurements based on discussions of Businger (1963), the relative importance of convection and temperature effects on ET and CER measured with the portable chamber has not been fully evaluated. Other concerns about the chamber technique for measuring gas exchange around individual leaves have been discussed by Jarvis (1970) and Idso et al. (1988). The main disadvantages of any chamber system are the inability to reproduce natural air movements present in a field canopy and the rapidly changing leaf temperature, ambient humidity, and CO_2 concentrations during the period of measurement. In this study we are concerned with a closed chamber system with no control over water vapor increase or CO_2 decrease and the internal microclimate.

The objective of this work is to describe a portable chamber for measuring ET on field plots and to show its utility for evaluating irrigation scheduling criteria for different crop species and different soil and plant management practices.

2. Material and methods

Construction details of a portable chamber that permit ET measurements over small corn (*Zea mays* L.) and soybean (*Glycine max* L. Mer.) have been previously discussed by Reicosky and Peters (1977). This configuration allows measurements over solid seeded crops as well and is suitable for several horticultural crops with similar canopy architecture. 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 farm tractor. The tractor transports the chamber and associated recording equipment from plot to plot, along with a portable generator that enables measurements in remote field locations. Preliminary calibration for ET measurements was described in detail by Reicosky and Peters (1977). The portable chamber was used to measure the rate of water loss from soybean grown in a hydroponic system designed to accurately measure water uptake. Results showed a linear relationship between the chamber measured transpiration and the absorption measured by the hydroponic system, suggesting the portable chamber accurately measured transpiration.

Additional calibration work was done by comparing the portable chamber directly to a precision weighing lysimeter (Reicosky et al., 1981). Measurements of ET were made on alfalfa that was approximately 0.7 m tall with complete ground cover and full canopy. There was no visible difference between the canopy in the lysimeter and the chamber measurement area located about 10 m from the weighing lysimeter. The lysimeter and the surrounding area were irrigated with 50 mm of water the preceding day and measurements made with the portable chamber periodically from sunrise to sunset. Results showed that ET measured by both the weighing lysimeter and portable chamber went through the expected diurnal patterns on an hourly basis and agreed with potential ET calculated using the Penman Combination Equation after Van Bavel (1966). Both hourly and daily values of ET showed reasonable agreement between the chamber and lysimeter, indicating the portable chamber approximates ET measured by the weighing lysimeter (Reicosky et al., 1981).

Recent improvements to the portable chamber technique for increased sensitivity have included an infrared gas analyzer for H_2O vapor and CO_2. A BINOS-Model 4B.2 (Leybold Hereaus) infrared gas analyzer (IRGA) was used to measure CO_2 and H_2O vapor concentrations in the differential mode (range of $\pm$ 50 μmol mol^{-1} of CO_2 and $\pm$ 10,000 μmol mol^{-1} of H_2O). For simplicity only water vapor data will be discussed. The air within the chamber was mixed with four fans at the rate of 13.2 m^3 min^{-1} each and the gas sample pumped to the IRGA through a 6.35 mm ID polypropylene at 34 l min^{-1}. A portion of the gas was subsampled at 2.5 l min^{-1} for analysis by the IRGA. Another portion of the sample gas was drawn off to a 65-l reference tank at 2.5 l min^{-1} to isolate and buffer fluctuations in the reference gas. Ambient air was used as the reference gas to follow diurnal fluctuations in gas concentration that were as large as 5,000 μmol mol^{-1} for H_2O vapor. During the 80-second data collection period, analog output from two channels of the IRGA and air temperature and radiation data were recorded every 2 seconds via a computer-controlled data acquisition system contained in an instrument shelter mounted on the back of the tractor. The IRGA analog 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 of H_2O vapor concentrations. Within the 80-second data collection period, a 30-second calculation window or interval was selected to calculate CER and ET. After correcting for the appropriate lag in getting the gas sample back to the analyzer and the canopy mixing lag, linear regression was used to calculate rate of H_2O vapor increase for use in calculation of

ET. Recent modifications have decreased the total sampling time from 80 seconds to 60 seconds, still using a 30-second calculation window.

The concentration regression method was used to calculate ET as described by Reicosky et al. (1989). In the concentration regression method used by Meyer et al. (1987) the rate of change of the mass of the gas with respect to time is estimated as a slope of the least squares line relating individual concentrations to time. The rate of change of the gas concentration converted to a mass basis, corrected for temperature and pressure using the ideal gas law is used in the regression. This rate is multiplied by the ratio of the chamber volume divided by the soil area to express the generation of H_2O vapor per unit land area and equated to ET. Details on the methods of calculation are discussed by Reicosky et al. (1989).

The current interest in irrigation scheduling places emphasis on field-measured ET related to leaf water potential (ψ_l) and air temperature within the canopy minus the air temperature above the canopy. Measurements were made periodically on a larger tillage irrigation study where the objective was to evaluate conventional tillage and no tillage systems on a Sioux sandy loam (Family sandy skeletal mixed, subgroup Udorthentic Haploboroll in the USDA-SCS Soil Classification System). A corn and soybean rotation was used with one-half the plots irrigated in 50-mm increments when the soil matric potential at the 0.3-m depth was equal to -30 kPa for a total of 698 mm in the 1988 growing season. Corn and soybean were planted on 5 May 1988 (DY 126) using a conventional row planter and fertilized at the rate of 291, 29, and 29 kg ha^{-1} of N, P, and K, respectively. The 1988 growing season provided a unique opportunity because it was a severe drought year with below-normal rainfall (only 330 mm during the growing season). Due to the severity of the drought, the differences between conventional till and no-till treatments for both irrigated and nonirrigated plots were not discernible. Throughout the following discussion tillage treatments are combined and only differences due to irrigation will be presented.

Chamber measurements of ET were compared with several other measurements of plant water stress to determine their relative sensitivity as irrigation scheduling tools. Leaf water potential (ψ_l) was measured using the pressure chamber technique described by Scholander et al. (1965). The terminal 30 cm of the uppermost fully exposed corn leaves and fully developed trifoliate of soybean were used for pressure chamber measurement. The leaf tissue was completely enclosed in a plastic bag lined with moist towels to maintain high humidity prior to excision. The enclosed leaf tissue was cut and the plastic bag containing the leaf tissue inserted into a larger plastic bag and quickly transported to the pressure chamber. The ψ_l was determined, using a pressurization rate of .05 MPa s^{-1} with the endpoint reading generally completed within 2 minutes after excision. These samples for ψ_l measurements were taken adjacent to the location and at the same time the chamber measurements were made.

Air temperatures within and above the plant canopy were measured in the center of the 15.3 by 15.3-m plots using copper-constantan (Type T) thermocouples. Data were recorded hourly on a computer-controlled data acquisition system following the technique described by Reicosky et al. (1980). The air temperature sensors were shielded from direct radiation in two concentric white PVC tubes with the in-canopy sensor fixed at 15 cm above the soil and the above-canopy sensor located 60 cm above the canopy and elevated weekly as the canopy height increased. The shields were 30 cm long and consisted of a 5.1 cm ID inner tube and a 6.4 cm ID outer tube. The air temperature sensors were set in the canopy shortly after planting. The difference between the in-canopy and the above-canopy temperature at the hour closest to the time of the chamber measurement was used in this work.

Throughout this study all data comparisons were made during midday under maximum evaporative demand ±3 hours of solar noon with the majority ±2 hours of solar noon to minimize radiation effects. Days selected for analysis were essentially cloud-free during midday with photosynthetically active photon flux density (PPFD) greater than 1000 μmol m^{-2} s^{-1}. The days selected were during peak plant activity and covered the 45-day period from 15 days (54 days after planting) pre-anthesis on corn to 30 days post-anthesis. During this period both irrigated corn and soybean had leaf area index (LAI) >3.0 with no visible signs of senescence.

Days were also selected to be greater than two days from rainfall greater than 5 mm or irrigation to minimize soil evaporation and respiration components of the net gas exchange.

The sensitivity of the chamber was evaluated by making measurements of soil evaporation on an extremely dry Dolan silt loam (Family fine loamy mixed Udic Haploboroll) on the West Central Experiment Station of the University of Minnesota. Soil evaporation was measured on bare plots with no actively growing vegetative material. Two plots were identified for evaporation measurements--one with a slight weed problem was raked shallow (2-cm depth) for weed control that resulted in a fine mulch on the surface of the soil. A second area was weed-free but had large surface cracks (≈1 cm wide) from drying of the expanding-type clay in this soil.

3. Results and discussion

Chamber measurements at low rates of evaporation in the absence of any plants showed different soil evaporation rates from the "cracked" soil and mulched soil in table 1. The evaporation rate from the cracked soil was consistently larger earlier in the season; however, the differences tended to decrease as the dry season progressed (data not shown). 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. In the case of the mulched soil, the gravimetric water content only changed slightly in the surface layers as a result of less evaporation. The practical implications of this small difference in evaporation 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 repeatability of the chamber at low evaporation rates.

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

	Midday Soil Evaporation - mm hr^{-1}	
Sample	"Raked"	"Cracked"
1	.089	.138
2	.074	.137
3	.072	.109
4	.066	.102
5	.067	.111
Mean	.074	.119
Std. Dev.	.009	.017

Midday leaf water potential (ψ_l) measured using the pressure chamber technique and ET measured using the portable chamber for corn is summarized in figure 1. As expected for the plants that experience more stress, ψ_l showed a gradual decrease related to a decrease in ET. There was a slight curvilinear relationship between the ψ_l and ET with the nonirrigated plants showing the lowest ET and ψ_l. There was some scatter among the data from irrigated plots where ψ_l decreased to approximately -1 MPa while ET ranged between .5 to 1.0 mm hr^{-1}. The change in ET was larger than the change in ψ_l for the irrigated plots while the change in ψ_l was larger than the change in ET for nonirrigated plots.

A similar relationship for soybean is shown in figure 2. The decrease in the ψ_l was related to the decrease in ET under full canopy conditions. However, this needs to be interpreted with caution because of the limited canopy development on the nonirrigated plots. The larger ET was measured on the irrigated plots and ranged from .5 to 1.0 mm hr^{-1} with the minimum ψ_l

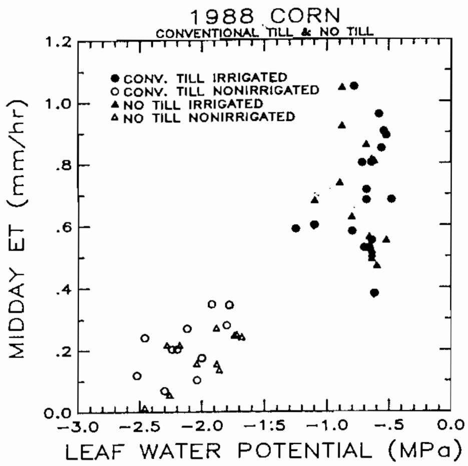

Figure 1 - Midday ψ_l versus ET for nonirrigated and irrigated corn.

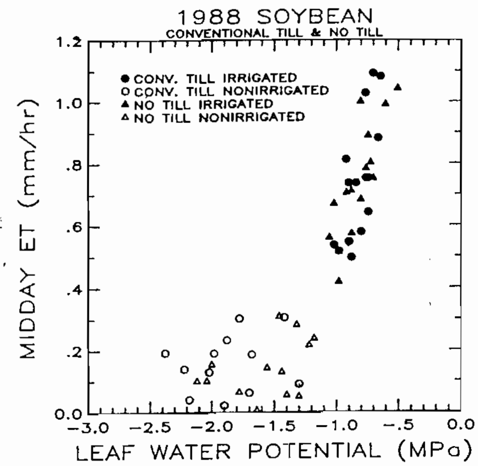

Figure 2 - Midday ψ_l versus ET for irrigated and nonirrigated soybeans.

of about -1 MPa. The nonirrigated ET was as large as 0.3 mm hr^{-1} and ψ_l ranged from -1.4 to -2.4 MPa. There was a general relationship where ψ_l decreased as ET decreased similar to corn in figure 1 that gives some indication of plant response to stress. Some of the scatter is due to varying evaporative demand, spatial variability, and the small piece of plant tissue used for measuring ψ_l that does not reflect the large number of plants spatially averaged with the portable chamber.

The difference between in-canopy air temperature and above-canopy air temperature was suggested by Reicosky et al. (1980) as a possible indicator of plant water stress for soybean. An example for corn on 18 July 1988 (DY 200) is shown in figure 3. The diurnal pattern of the in-canopy temperature minus the above-canopy temperature for irrigated corn ranged from near 0 at dawn to -2 or -3 °C during midday. The nonirrigated corn was near 0 during the night but showed a maximum of +5.5 °C at hour 13. The canopy temperature difference showed positive values for the nonirrigated plots, indicating that the air temperature within the canopy was substantially higher than the air temperature above the canopy under high evaporative demand. These measurements were obtained under complete canopy with LAI of at least 3 in the irrigated plots, whereas LAI on the nonirrigated plots ranged from 1.5 to 2. These results are expected due to the severe soil water stress and the incoming energy not being dissipated by evaporating water as in the case of the irrigated plots. For the nonirrigated plots, the incoming energy is dissipated by heating the soil and plant and results in a higher air temperature in the canopy when there is insufficient water to meet the evaporative demand.

These air temperature differences within the canopy of corn suggest a simple method for determining the onset of plant water stress provided turbulent mixing in the canopy is not severe. When the air temperature in the canopy approaches that above the canopy, water can be applied to meet the evaporative demand. The relationship between ET and the canopy air temperature difference is summarized in figures 4 and 5 for corn and soybean, respectively. In both cases, the irrigated and nonirrigated plots segregated into two distinct groups that showed high ET was associated with cooler air temperature in the canopy. The relationship was similar for corn and soybean with the scatter in the data precluding a crop difference. The same qualitative relationship was observed for CER (data not shown) versus the canopy air temperature difference for both corn and soybean, with the corn quantitatively having a higher CER than soybean.

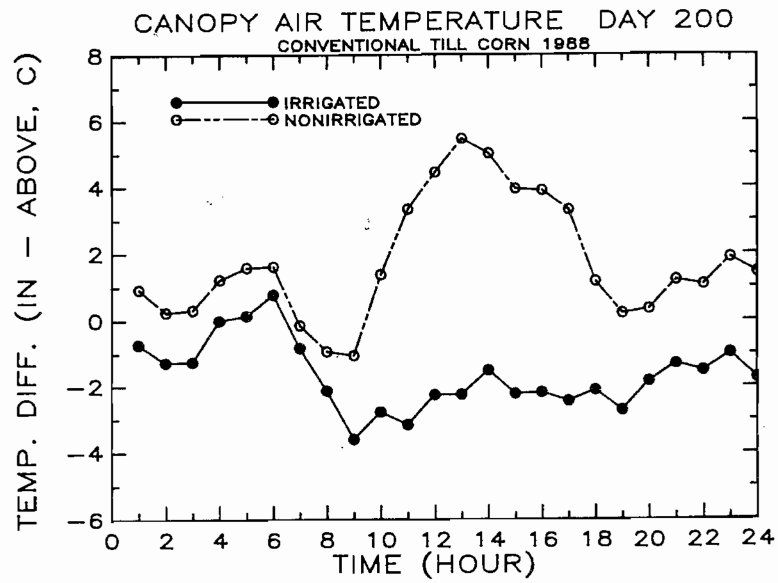

Figure 3 - An example of the in-canopy temperature minus the above-canopy temperature for irrigated and nonirrigated corn on 18 July 1988.

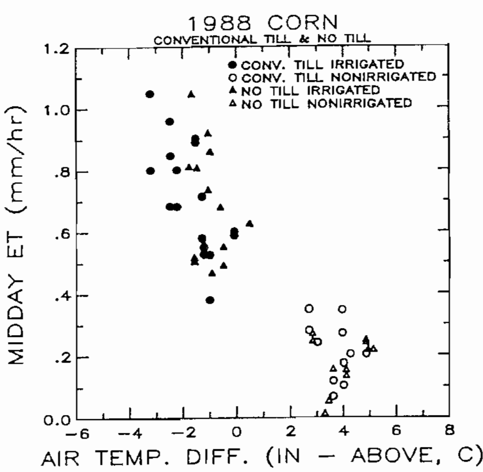

Figure 4 - Midday ET versus the difference between the in-canopy air minus the above-canopy air temperature for corn.

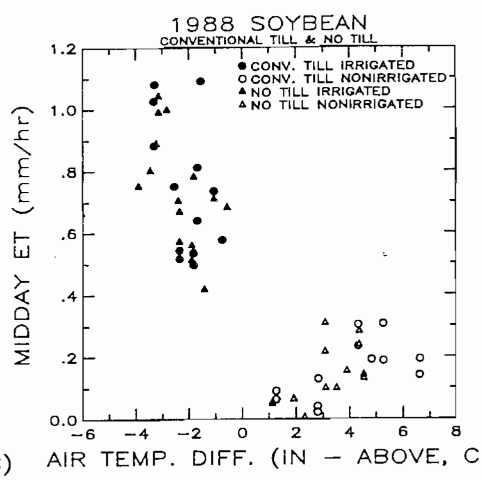

Figure 5 - Midday ET versus the difference between the in-canopy air temperature minus the above-canopy air temperature for soybean.

4. Conclusions

Increased pressure to improve crop water use efficiency requires improved methods for measuring crop water use in the field. The portable chamber can serve as a useful research tool in developing and evaluating irrigation scheduling criteria. The incorporation of an infrared gas analyzer for both water and carbon dioxide results in increased sensitivity as reflected in low soil evaporation rates. Leaf water potential and ET decreased progressively as the soil water deficit increased on the nonirrigated plots during the severe drought of 1988. The ET on stressed plots was 10 to 20% of that on the irrigated plots when the in-canopy air temperatures were 4 to 6° C higher than the above-canopy temperature. The relationship between ET and leaf water potential and in-canopy air temperature as the soil water deficit became more severe suggest the chamber can be used to evaluate other irrigation scheduling techniques. Improvements in the equipment for measuring water vapor and carbon dioxide exchange, automatic data collection, and methods of calculation have resulted in improved accuracy. Further study using the portable chamber should lead to better irrigation scheduling criteria for a wide range of soil and plant management systems.

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