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Accuracy of Lysimetric, Energy Balance, and Stability-corrected Aerodynamic Methods of Estimating Above-canopy Flux of CO_2[1]

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ABSTRACT

Measurement of carbon dioxide exchange is necessary to indicate rates of photosynthesis in the field. Methods which are accurate over short periods of 15 min to 1 hour can indicate the influence of changing weather conditions on crop photosynthetic activity. Three micrometeorological methods—the lysimetric, energy balance, and stability-corrected aerodynamic—can be used for field determination of the flux of CO_2 to a crop surface. The objective of this paper is to present a detailed comparison of the performances of the three methods. Measurements were made in an oat field at Mead, Neb. Results obtained with the three methods were in good agreement, both on a short-period and on a daily basis. The calculated CO_2 flux agreed reasonably well with estimates from other oat-photosynthesis studies. Midday CO_2 flux rates ranged from about 2 to 3 $\times 10^{-7}$ g cm^{-2} sec^{-1}. The three micrometerological methods were subjected to detailed error analysis to evaluate the relative influence of errors in measurement of the constituent input parameters used to calculate the flux of carbon dioxide, namely water vapor flux and gradients of vapor pressure and CO_2 concentration in the lysimetric method; net radiation, soil heat flux and gradients of vapor pressure, air temperature and CO_2 concentration in the energy balance method; and gradients of windspeed, air temperature and CO_2 concentration in the stability-corrected aerodynamic method.

Additional index words: **Micrometeorology, Microclimate, Energy balance, Lysimeters, Aerodynamic, CO_2 Flux, Error analysis, Field-photosynthesis, Stability correction, Exchange coefficients, Turbulent transfer.**

We wish to know the influence of changing weather conditions and the influence of microclimate and/or plant architecture alterations on the water use efficiency. To do so it is necessary to make short period measurements of photosynthesis and evapotranspiration simultaneously.

Precision weighing lysimeters are adequate for the short period determination of evapotranspiration rates under field conditions (van Bavel and Myers, 1962; Tanner, 1967; Rosenberg et al., 1968). An energy balance approach utilizing the Bowen Ratio concept has also been shown to agree with the lysimetrically measured fluxes within acceptable limits (Tanner, 1960; Denmead and McIlroy, 1970; Blad and Rosenberg, 1974). Less progress has been made, however, in rapid, short-period determination of photosynthesis in the field.

Non-meteorological methods have been proposed by Thomas and Hill (1949) and Baker and Musgrave (1964). These workers have used plastic chambers to enclose small portions of a field in order to measure the exchange of CO_2 between air and crop. The use of such chambers may, however, drastically disturb the plant microenvironment. Despite the fact that controlled environment chambers and cuvettes of quite elaborate design have been developed (for example, see Lange et al., 1969) results obtained with such equipment will remain of limited utility until they are compared with results of open field micrometeorological measurements made simultaneously.

Three micrometeorological tools for field determination of the flux of CO_2 (F_c) to a crop surface are considered in this paper. These are the lysimetric, the energy balance and the aerodynamic methods. All are founded on Fick's law of diffusion:

$$F_c = f\, K_c \frac{\partial c}{\partial z} \qquad [1]$$

where F_c = CO_2 flux, K_c = turbulent exchange coefficient for CO_2, and c = CO_2 concentration at height z. In order to use any of these methods in determining F_c it is customary to assume that the exchange coefficient for CO_2 (K_c) is equal to either the exchange coefficient for water vapor (K_w), sensible heat (K_h) or momentum (K_m).

In the *lysimetric method*, K_w is computed directly from water vapor flux measured with precision weighing lysimeters and vapor pressure gradients measured over the evaporating surface with appropriate sensors [e.g., by aspirated, shielded thermocouple psychrometers (Rosenberg and Brown, 1974)]:

$$K_w = \frac{LE}{60 \frac{M_w/M_a}{P} L\rho \frac{\partial e}{\partial z}} \qquad [2]$$

where LE = latent heat flux, L = latent heat of vaporization, E = water vapor flux, ρ = air density, P = atmospheric pressure, and M_w, M_a = molecular weights of water and air, respectively. F_c is obtained (assuming $K_c = K_w$) as the product of K_c and CO_2 gradients measured in the same elevation increment described by K_w.

The *energy balance approach* (e.g., Denmead, 1969) assumes the identity of K_c, K_w, and K_h. Exchange coefficients are obtained from a functional relation involving net radiation (Rn), soil heat flux (S) and gradients of vapor pressure ($\frac{\partial e}{\partial z}$) and air temperature ($\frac{\partial T}{\partial z}$):

$$K = \frac{-(Rn+S)}{60(\rho C_p \frac{\partial T}{\partial z} + \frac{M_w/M_a}{P} L \frac{\partial e}{\partial z})} \qquad [3]$$

F_c can then be obtained from equations [1] and [3].

Inoue et al. (1958) and Lemon (1960) attempted to develop *aerodynamic* estimates of F_c by equating K_c with the exchange coefficient for momentum (K_m). K_m was calculated from relationships based on logarithmic windspeed profiles. These relationships are, however, strictly valid for neutral conditions which prevail, generally, for very short periods of time. Under non-neutral conditions these assumptions may lead to significant errors. *Stability corrections* must be applied to aerodynamic methods if flux estimates are to be correct. Assuming K_w = K_c, equation [1] becomes: $F_c = f\, K_w \frac{\partial c}{\partial z} = f\, K_m \left(\frac{K_w}{K_m}\right) \frac{\partial c}{\partial z}$,

$$\text{or } F_c = f\, k^2 z^2 \left(\frac{\partial U}{\partial z}\right) \left(\frac{\partial c}{\partial z}\right) \left[(\phi_m^{-2}) \left(\frac{K_w}{K_m}\right)\right] \qquad [4]$$

where wind speed gradient $\frac{\partial U}{\partial z} = \frac{u}{kz} \phi_m$, with u = fric-

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tion velocity $= (\tau/\rho)^{1/2}$; $\tau =$ shear stress; $\phi_m =$ non-dimensional wind shear (or diabatic correction factor for the log-law wind profile, $\partial U/\partial z = u\ /kz$), $K_m = \frac{u^{2}}{(\partial U/\partial z)} = k^2z^2(\phi_m)^{-2}\ \partial U/\partial z$, k = von Karman's constant. Both ϕ_m and K_w/K_m have been found to vary with atmospheric thermal stability, which is usually expressed in terms of the Richardson number, Ri. In this study we use stability corrections proposed in some recent micrometeorological investigations (Businger, 1966; Dyer, unpublished; Dyer and Hicks, 1970; Webb, 1970; Pruitt, Morgan, and Lourence, 1973):

1. Model of Pruitt et al. (1973) ~~(hereafter called the PML model)~~:
$\phi_m = (1 - 16\ Ri)^{-1/3}$ for unstable stratification,
$= (1 + 16\ Ri)^{1/3}$ for stable stratification;
$K_w/K_m = 1.13\ (1 - 60\ Ri)^{0.074}$ for unstable stratification,
$= 1.13\ (1 + 95\ Ri)^{-0.11}$ for stable stratification
$k = 0.42.$ [5]

2. Model of Businger (1966) and Dyer (unpublished) (hereafter called ~~the B-D model~~):
$\phi_m = (1 - 16\ Ri)^{-0.25}$ for unstable stratification,
$= (1 - 5.2\ Ri)^{-1}$ for stable stratification;
$\frac{K_w}{K_m} \approx \frac{K_h}{K_m} = (1 - 16\ Ri)^{0.25}$ for unstable stratification,
$= 1$ for stable stratification;
$k = 0.40.$ [6]

Gradients (or derivatives with respect to height) for the various profiles of e, T, c and U were evaluated using finite differences in the manner suggested by Panofsky (1965). If Ψ is a profile variable, then the gradient is given by:

$$\frac{\partial\psi}{\partial z} = \frac{\psi_2 - \psi_1}{\sqrt{z_1 z_2}\ \ln\left(\frac{z_2}{z_1}\right)} \qquad [7]$$

where z_1 and z_2 are the heights above the ground. This approximation is, of course, rigorous for logarithmic profiles. Using this approximation and introducing the concept of zero plane displacement, d, we find that eq. [4] becomes:

$$F_c = \rho k^2\ \frac{(U_2 - U_1)(c_2 - c_1)}{\left(\ln\frac{z_2 - d}{z_1 - d}\right)^2}\ \left(\phi_m^{-2}\ \frac{K_w}{K_m}\right), \qquad [8]$$

Below we present a detailed comparison of lysimetric, energy balance and aerodynamic (stability corrected) estimates of F_c over an oat field. We find that the three methods compare well on both a short period (30 min) and a daily basis. The calculated CO_2 flux rates agree reasonably well with results from other studies of oat photosynthesis.

In this paper we also give a detailed error analysis of the three micrometeorological methods. Perhaps disagreements concerning the usefulness of the micrometeorological methods (e.g. Wright and Brown, 1967; Harper et al., 1973) may have been due, at least in part, to artifacts or experimental errors of a nature exposed by the analyses we discuss. The error analysis should serve as a useful tool, in its own right, for investigators considering the use of micrometeorological methods in estimating field photosynthesis since the instrumental accuracies required are clearly established.

ERROR ANALYSIS

The magnitude of errors (or a measure of uncertainty-interval) in the calculation of F_c due to errors in measurement of the constituent input parameters are estimated employing the root sum square error analysis technique (Kline and McClintock, 1953; Blad and Rosenberg, 1974). Using eq. [1], we find that the relative error in F_c, $(\sigma F_c/F_c)$, is estimated by:

$$\frac{\sigma(F_c)}{F_c} = \left[\left\{\frac{\sigma(K_c)}{K_c}\right\}^2 + \left\{\frac{\sigma(\Delta c)}{(\Delta c)}\right\}^2\right]^{\frac{1}{2}} \qquad [9]$$

The relative error in exchange coefficient is obtained from eqs. [3] and [2] as follows:

$$\frac{\sigma(K_c)}{K_c} = \left[\left\{\frac{\sigma(Rn + S)}{(Rn + S)}\right\}^2 + \left\{\frac{m_1\ \sigma(\Delta T)}{m_1(\Delta T) + m_2(\Delta e)}\right\}^2 + \left\{\frac{m_2\ \sigma(\Delta e)}{m_1(\Delta T) + m_2(\Delta e)}\right\}^2\right]^{\frac{1}{2}} \qquad [10]$$

for the energy balance method, where $m_1 = 60\rho\ C_p = 0.0165$ and $m_2 = 60\rho\left(\frac{M_w/M_a}{P}\right) L = 0.0254.$

For the lysimetric method the relative error in exchange coefficient is:

$$\frac{\sigma(K_c)}{K_c} = \left[\left\{\frac{\sigma(LE)}{LE}\right\}^2 + \left\{\frac{\sigma(\Delta e)}{\Delta e}\right\}^2\right]^{\frac{1}{2}} \qquad [11]$$

where Δe, Δc, and ΔT are, respectively, the gradients of vapor pressure, CO_2 concentration, and air temperature in the layer of air (in our case between 1.0 and 2.0 m) above ground.

Energy Balance Method

Figure 1 shows the relative errors in F_c when the energy balance method is used to compute a value of K_c. The following set of input errors was considered in the preparation of this figure: $\sigma(Rn) \approx \sigma(Rn+S) = 0.02$ ly min^{-1}, $\sigma(\Delta T) = 0.025$C, $\sigma(\Delta e) = 0.1$ mb, and $(\Delta c) = 0.1$ ppm. $(\sigma F_c)/F_c$ is shown as a function of vapor pressure gradients (Δe) for two conditions of CO_2 gradients ($\Delta c = 1$ and 5 ppm), and four conditions of air temperature gradient ($\Delta T = -0.1$, 0.1, -0.3 and 0.3 C). These conditions cover the daytime range of Δe, ΔT, and Δc normally encountered in the east central Great Plains region.

For non-advective conditions[3] (sensible heat generation at the surface, negative ΔT) and moderate vapor pressure gradients ($\Delta e = -0.6$ to -1.0 mb), the relative error in F_c ranges from 10 to 15%. The error is greater, ranging from 20 to 25% for conditions of strong sensible heat advection (sensible heat consumption at the surface, positive ΔT; e.g. $\Delta T = 0.3$ C) and moderate vapor pressure gradient. The percentage error is reduced by 3% when Δc is increased from 1 to 5 ppm.[4] When the vapor pressure gradient is small ($\Delta e = -0.4$ mb), the error increases to 17 to 24% in the non-advective case and 30 to 50% in the advective case. Magnitude of the net radiation and soil heat flux, in the range studied, had no significant effect on the value of $\sigma(F_c)/F_c$.

The errors in input parameters assumed in preparation of Fig. 1 are quite reasonable and performance within these limits is achievable with careful instrument calibration and maintenance. In Fig. 2 effects of larger input errors are considered. In this example, the errors in Rn, Δe, ΔT and ΔC are increased individually by about 2 to 2.5 times the value used in Fig. 1. Increases, singly, in $\sigma(Rn)$ and $\sigma(\Delta T)$ have no significant effect. However, the effect on increased $\sigma(\Delta e)$ is substantial. When vapor pressure gradient is moderate, doubling the error in Δe leads to a 7 to 13% increase in $\sigma(F_c)/F_c$ under non-advective conditions, and to a 10 to 17% increase under mildly advective conditions. When vapor pressure gradient is low, doubling the error in Δe increases $\sigma(F_c)/F_c$ by 25 to 30%. The effect on an increase in $\sigma(\Delta c)$ on $\sigma(F_c)/F_c$ can range from 4 to 9% depending upon whether Δc is small or large. The effects are similar for other cases of Rn + S and ΔT. Under a combination of strongly advective conditions and low vapor pressure gradient, however, this method is subject to large errors. This combination of environmental conditions is quite uncommon, however, and is not shown in the figure.

Lysimetric Method

Relative errors in F_c applicable to the lysimetric method are shown in Fig. 3 and 4. In Fig. 3 the following set of input errors were used:

$\sigma(LE) = 0.02$ ly min^{-1} (for LE measured over 30 min),
$\sigma(\Delta e) = 0.1$ mb, and $\sigma(\Delta c) = 0.1$ ppm.

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[3] A detailed discussion of the significance of advective and non-advective conditions is given in a recent paper by Blad and Rosenberg (1974).

[4] $(\sigma F_c)/F_c$ is expressed throughout this paper in terms of percentage, i.e. 0.4 = 40%. Alterations in the value of $(\sigma F_c)/F_c$ due to changes in the independent variables are expressed as changes in the absolute percentage. For example, when Δc is increased from 1 to 5 ppm, $(\sigma F_c)/F_c$ ranges from 7 to 12% under non-advective conditions, and 17 to 22% for conditions of strong sensible heat advection. (With the set of input errors given above.)

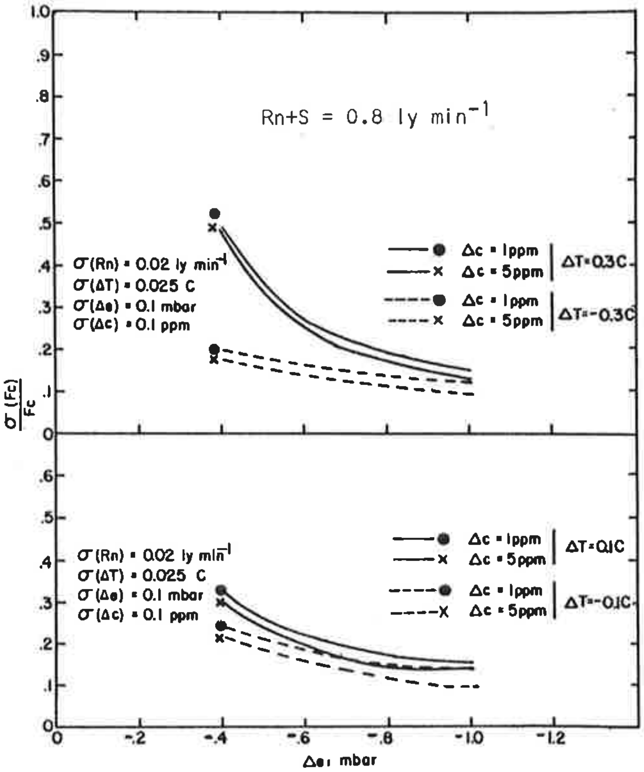

Fig. 1. Relative errors in F_c calculated by the energy balance method for the range of assumed errors in input parameters and the range of ambient conditions indicated (Rn = 0.8 ly min⁻¹).

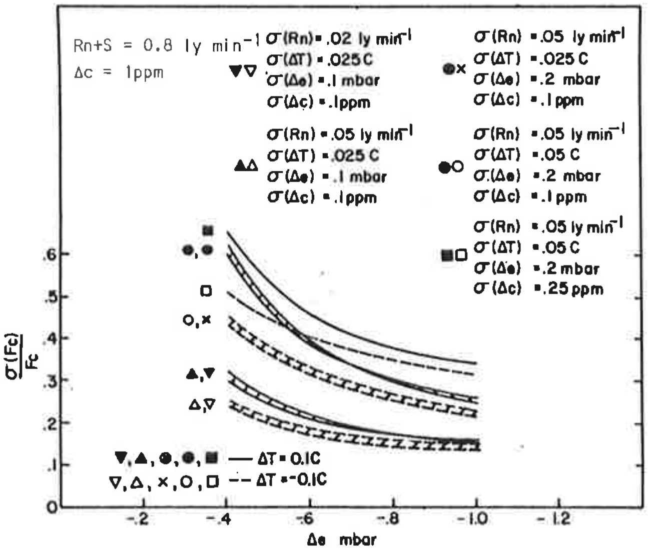

Fig. 2. Relative errors in F_c by the energy balance method for a range of increasing errors in input parameters and for the ambient conditions indicated (ΔC = 1 ppm). Cross-hatched bands the data sets indicated by the symbols to the left.

When vapor pressure gradient is moderate and LE flux and Δc are strong, the error in F_c ranges from 10 to 16%. With weak LE flux and Δc the error ranges from 16 to 21%. However, with low vapor pressure gradient, $\sigma(F_c)/F_c$ is about 25 to 28%. In each case, the error is reduced by 3 to 4% when strong Δc is substituted for smaller values.

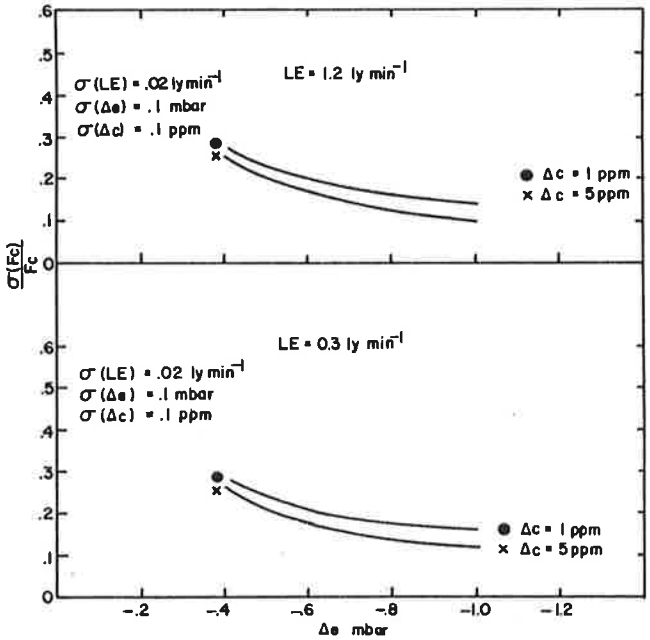

Fig. 3. Relative errors in F_c calculated by the lysimetric method for the ambient conditions and input errors specified. LE flux of 1.2 and 0.3 ly min⁻¹ shown.

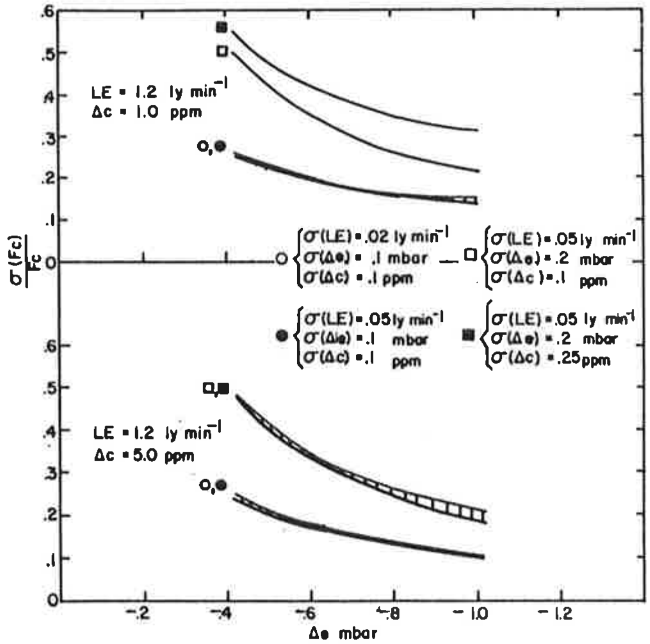

Fig. 4. Relative errors in F_c. Same as Fig. 3 for a range of increasing errors in input parameters and for the ambient conditions indicated (LE flux of 1.2 ly min⁻¹ only).

Under most experimental circumstances the errors in input parameters assumed in the preparation of Fig. 3 are achievable. Figure 4 shows the effect in increasing σ(LE), σ(Δe), and σ(Δc) to 0.05 ly min⁻¹, 0.2 mb, and 0.25 ppm, respectively. Increasing these errors individually leads to similar effects as in the case of the energy balance method. Increase in σ(LE) has no significant effect on the value of $\sigma(F_c)/F_c$. An increase in σ(Δe) causes a 7% increase in $\sigma(F_c)/F_c$ when Δe is moderate and a 24% increase when Δe is low. The effect of increase in σ(Δc) is 5 to 9% if Δc is small, and negligible if Δc is large.

Aerodynamic Method

The error in F_e applicable to the aerodynamic method is computed in a slightly different way. For a given set of input parameters, ΔU, Δc, ΔT, T and d, the value of F_c is computed using eqs. [8], [5] and [6] as described earlier. Assuming $\sigma(\Delta U)$, $\sigma(\Delta c)$, $\sigma(T)$ and $\sigma(d)$ as the errors in input parameters, a new value, F_c', is obtained from the same set of equations by substituting $\Delta U + \sigma(\Delta U)$ for ΔU, $\Delta c + \sigma(\Delta c)$ for Δc, $\Delta T + \sigma(\Delta T)$ for ΔT, $T + \sigma(T)$ for T and $d + \sigma(d)$ for d. The relative error in F_c is defined as $\sigma(F_c)/F_c = F_c' - F_c/F_c$. The error in aerodynamic estimates of F_c, thus defined, was computed with sets of input parameters of varying magnitude and their associated errors. Assuming $\sigma(\Delta U) = 5$ cm/sec, $\sigma(\Delta c) = 0.1$ ppm, $\sigma(\Delta T) = 0.025$ C, $\sigma(T) = 0.2$ C and $\sigma(d) = 3$ cm, values of $\sigma(F_c)/F_c$ ranged from 1 to 2% for large ΔU and Δc (1.2 m sec^{-1} and 5 ppm) and from 4 to 25% for small ΔU and Δc (0.4 m sec^{-1} and 1 ppm). The effect of doubling input errors is insignificant in the case of strong gradients of U and c. However, with weak gradients the value of $\sigma(F_c)/F_c$, may range from 14 to 20% in conditions of atmospheric instability (negative Ri) and from 30 to 75% in conditions of atmospheric stability (positive Ri).

At first sight, the error inherent in the aerodynamic method does not seem severe. It should be emphasized, however, that superimposed on the error calculated above is an uncertainty in the empirical expressions for the stability correction factor ($\phi_m^{-2} K_c/K_m$). This uncertainty can easily lead to an additional 10 to 20% error in estimation of F_c.

EXPERIMENTAL AND COMPUTATIONAL PROCEDURES

Field measurements of evapotranspiration and CO_2 fluxes were made during the period 30 Sept. 1972 to 10 Oct. 1972 at the University of Nebraska Agricultural Meteorology Research Laboratory (41° 09′ N; 96° 30′ W; 354 m above m.s.l.) located near Mead, Neb. The experimental field of about 2.55 ha was planted to oats (*Avena sativa* L., market mixture of 'Neal' and 'Dakota' cultivars) on 17 Aug. 1972 to provide field cover as well as a uniform greensward for instrumental calibrations. Fetch at the site of micrometeorological instrumentation was approximately 150 m to the south and 100 to 125 m to the southeast and southwest. Crop height during the study was about 40 to 50 cm.

CO_2 concentration ($[CO_2]$) and gradients (ΔCO_2) were measured with two Infra Red Gas Analyzers — a Beckman Model 315 for absolute analysis and a Grubb Parsons SB-2 for differential analysis. An automatic calibration system was developed to permit performance checks of both analyzers to be made hourly with a set of standard gases. Details of the sampling and analysis system are reported by Rosenberg and Verma.[5] CO_2 gradients measured between the elevations of 1.0 and 2.0 m above the ground were used in this study.

Air temperature and vapor pressure profiles were measured with thermocouple psychrometer assemblies described by Rosenberg and Brown (1974). Measurements were made at 1.0, 1.25, 1.50, and 2.0 m above the ground. Instrument function and accuracy of the psychrometer assemblies were checked once each hour by automatically moving all sensors into the same horizontal plane and noting the agreement in dry and wet bulb temperatures. Corrections were made during the later computational process.

Profiles of wind speed were measured with a set of 6 or 7 Casella-Sheppard type sensitive cup anemometers mounted at 0.75, 1.0, 1.25, 1.50, 1.75, 2.0, and 2.25 m above the ground.

The average values of LE measured with two improved van Bavel-Myers automatic precision weighing lysimeters (Rosenberg and Brown, 1970) were used in this study. Net radiation was measured with Swissteco type S1 and Middleton model CN6 net radiometers. Soil heat flux was obtained with Middleton heat flux plates buried 4 cm deep in the soil.

All meteorological measurements were made twice on the quarter hour. Data were logged on punched tape with an automatic analog-to-digital data system. These data were converted from the digitized emf or count record of individual sensors into parametric forms with a series of computer programs. All data were averaged over half-hour periods.

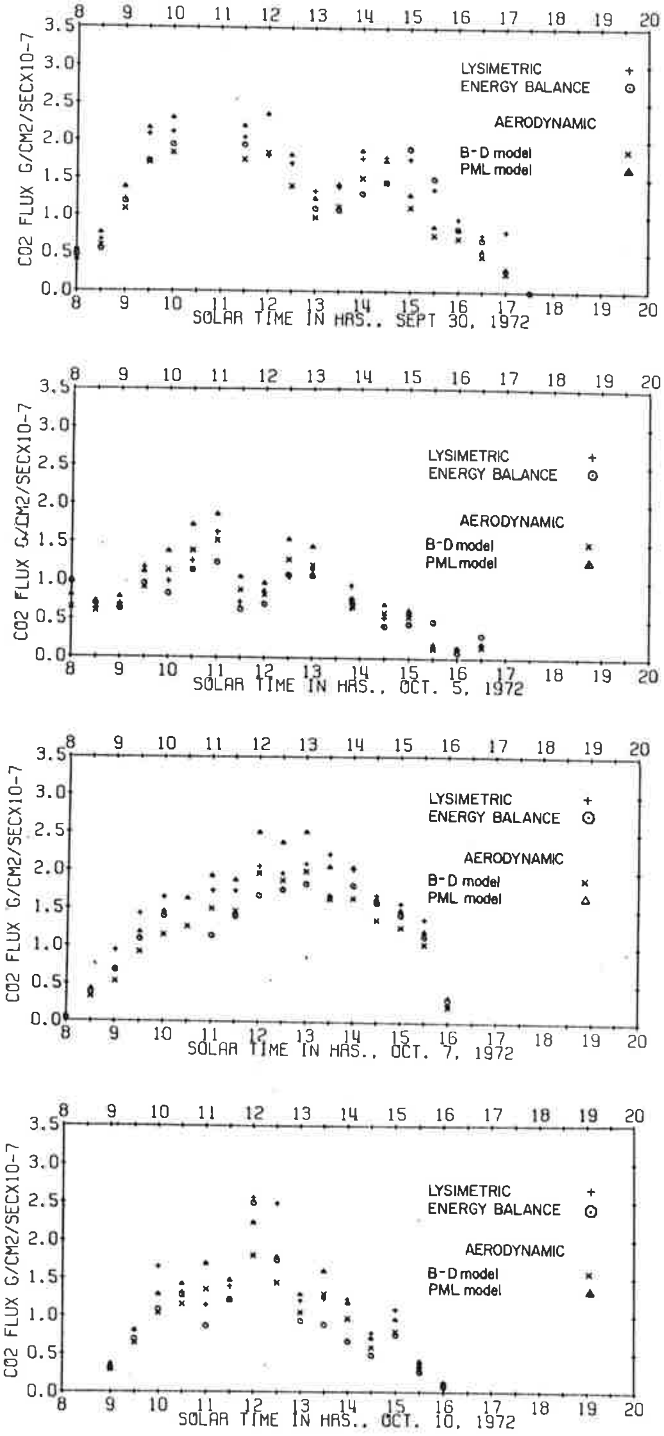

Fig. 5. CO_2 flux over oats at Mead, Neb., computed by the lysimetric, energy balance and two aerodynamic methods. A, 30 Sept. 1972; B, 5 Oct. 1972; C, 7 Oct. 1972; and D, 10 Oct. 1972.

Gradients of vapor pressure, CO_2, air temperature, and wind speed measured between 1.0 and 2.0 m above ground were used in calculating F_c. Lysimetric CO_2 flux was calculated with eqs. [1] and [2]. Energy balance estimates of F_c were obtained with eqs. [1] and [3]. Equation [8] was used to obtain F_c by the aerodynamic method. The stability correction factors proposed in eq. [5] (the PML model) and eq. [6] (the B-D model) were used. Values of Ri (based on virtual temperature) in the

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[5] A system and program for monitoring CO_2 concentration and gradients in an agricultural region. Submitted for Publication.

Table 1. Weather conditions at Mead, Neb., on days of oat photosynthesis observation.

Parameter	Units	Elevation	Date in 1972			
			30 Sept.	5 Oct.	7 Oct.	10 Oct.
		m				
Solar radiation	ly day^{-1}		471	172	456	188
Latent heat flux	ly day^{-1}		-281	-162	-230	-227
Max. temp.	C	2	22.9	21.4	23.0	23.8
Min. temp.	C	2	0.4	8.0	-6.6	12.7
Mean temp.	C	2	11.6	15.2	10.0	17.8
Max. vapor press.	mbar	2	11.4	15.7	14.3	20.9
Min. vapor press.	mbar	2	5.6	10.0	3.6	11.7
Mean vapor press.	mbar	2	9.0	13.6	8.2	15.9
Mean wind speed	m sec^{-1}	2	2.4	2.8	2.1	4.2

Table 2. Comparison of average daytime CO_2 fluxes (mg CO_2 dm^{-2} hr^{-1} or g cm^{-2} hr^{-1} $\times 10^6$) over oats at Mead, Neb., measured by three micrometeorological methods.

Days	Lysimetric Method	Energy Balance Method	Aerodynamic method	
			Businger-Dyer	Pruitt et al.
30 Sep 72	55.2	47.7	44.4	55.2
5 Oct 72	31.3	29.2	31.6	35.9
7 Oct 72	56.3	47.0	44.8	56.6
10 oct 72	44.7	35.5	35.7	43.7

air layer 1.0 to 2.0 m were computed from the profiles of wind speed, air temperature, and vapor pressure. These values (ranging from —0.06 to 0.02) were used to quantify the stability correction factor. Values of zero plane displacement, d, were obtained from several sets of wind speed profile measurements made under nearly neutral conditions.

RESULTS

Comparison of the Micrometeorological Methods in the Field

The CO_2 flux, computed with the three methods, is presented in Fig. 5A through 5D for four different days. (A summary of weather conditions on these days is given in Table 1). In view of the large number of independent data sets used and the different sources of error outlined in the previous section, the agreement in fluxes estimated by the three methods is good. We choose to consider the lysimetric method as the standard and most direct measure against which to compare the other methods. Both the energy balance method and the B-D aerodynamic methods tend to underestimate F_c by 10 to 20% and 10 to 30%, respectively. The PML aerodynamic method seems to overestimate F_c by 15 to 20% at times. Significantly better agreement is obtained when average daytime fluxes are considered (Table 2).

It should be noted that the fluxes of both water vapor or sensible heat will be similarly estimated by the three methods since these methods assume that $K_c = K_w = K_h$. Water vapor flux is underestimated by the energy balance method (Blad and Rosenberg, 1974). The PML aerodynamic model assumes that $K_w/K_m = 1.13$ under neutral conditions and that von Karman's constant k has a value of 0.42. The B-D model uses K_h/K_m ($= K_w/K_m$) $= 1.0$ under neutral conditions and $k = 0.40$. There is some evidence in the micrometeorological literature that K_w/K_m (or K_h/K_m) can be greater than 1.0 under neutral conditions (e.g. Businger et al., 1971). Use of K_w/K_m (or K_h/K_m) $= 1.10$ to 1.15 under neutral conditions will increase the Businger-Dyer stability correction factor by 10 to 15% which will, in turn, increase the predicted F_c values to more closely agree with the lysimetric estimates. Lysimeters provide the most direct and accurate measurement of water vapor flux. We must also note that, while their performance is generally better, the precision lysimeters at Mead may differ by 10 to 20% at times because of mechanical and/or crop uniformity problems. In view of these considerations the overall comparison between the lysimetric, energy balance, and aerodynamic methods of estimating CO_2 flux seems quite good.

Comparison With Other Studies

It is instructive to establish whether *any* of the methods tested provide estimates of F_c which are reasonable in terms of field photosynthesis. The literature on field photosynthesis by oats is not abundant. Criswell and Shibles (1971) determined the photosynthesis rate of flag leaves of 20 oat genotypes in an artificially lighted, water-jacketed chamber. Light intensity ranged from 0.43 to 0.24 ly min^{-1} (400 to 700 nm waveband). The rates of photosynthesis during 1 year of study ranged from 0.67 to 1.33×10^{-7} g CO_2 cm^{-2} (leaf area) sec^{-1} for these varieties and from 0.61 to 0.89×10^{-7} g CO_2 cm^{-2} (leaf area) sec^{-1} during a second year of study. Specific leaf dry weight ranged from about 0.36 to about 0.53 g dm^{-2} in the varieties tested during both years. If this chamber research realistically mimicks net photosynthesis in the field, we should expect peak field CO_2 flux rates to range from about 1.8 to 3.9×10^{-7} g cm^{-2} (ground area) sec^{-1} (assuming a reasonable value of leaf area/ground area of about 3). Our observations show that during midday these values are, indeed, realistic. The comparison is intended only as an order of magnitude check on our results.

SUMMARY AND CONCLUSIONS

Three micrometeorological methods, the lysimetric, energy balance and stability-corrected aerodynamic, were used to determine CO_2 exchange rates from oats under field conditions. Results of these methods were in good agreement, both on a short-period and on a daily basis. These estimates compared well with those from other oat-photosynthesis studies.

An error analysis of the lysimetric and energy balance methods reveals that errors in vapor pressure gradient can be important. Errors in CO_2 gradient are also important except when these gradients are strong. Errors in net radiation, air temperature gradient and lysimetrically measured water vapor flux are not important.

Under a set of given weather conditions the lysimetric method is normally subject to relatively smaller errors than is the energy balance method. Under conditions of strong sensible heat advection and with small vapor pressure gradients, the energy balance method is subject to large errors. This combination of conditions occurs very rarely, however.

The results of our error analysis and field tests show that althrough aerodynamic methods are frequently criticized, they can if properly corrected for stability conditions, be effectively used to estimate flux of CO_2. Errors are greatest under calm conditions. The uncertainly in the value of empirical constants used for stability corrections must also be considered.

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APPENDIX: NOTATION AND CUSTOMARY UNITS

A = sensible heat flux (ly min^{-1})
c = CO_2 concentration (ppm)
C_p = specific heat at constant pressure (cal gm^{-1} C^{-1})
d = zero plane displacement (cm)
E = water vapor flux (gm cm^{-2} min^{-1})
e = vapor pressure (mbar)
F_c = CO_2 flux (gm cm^{-2} sec^{-1})
f = conversion factor for CO_2 from ppm to specific weight
g = acceleration due to gravity (cm sec^{-2})
k = von Karman's constant
K_c, K_h, K_m, K_w = Exchange coefficients for CO_2, sensible heat, momentum and water vapor (cm^2 sec^{-1})
L = latent heat of vaporization (cal gm^{-1})
LE = latent heat flux (ly min^{-1})
Ri = Richardson number $= g(\frac{\partial\Theta_v}{\partial_z})/\Theta_v(\frac{\partial U}{\partial_z})^2$
Rn = net radiation (ly min^{-1})
S = soil heat flux (ly min^{-1})
T = air temperature (C or Absolute)
T_v = virtual temperature (C or Absolute)
U = wind speed (m sec^{-1} or cm sec^{-1})
u_* = friction velocity (m sec^{-1} or cm sec^{-1})
z = height above ground (cm or m)
M_w, M_a = molecular weight of water and air
$m_1 = 60\ \rho\ C_p = 0.0165$
$m_2 = 60\ \rho\ \frac{M_w}{M_a} L = 0.0254$
ϕ_m = diabatic correction factor
Ψ = a function
Θ = potential temp. (C or Absolute)
Θ_v = virtual potential temp. (C or Absolute)
τ = shear stress (gm cm^{-1} sec^{-2})
ρ = air density (gm cm^{-3})
Γ = adiabatic lapse rate (C cm^{-1})
σ = error in various parameters

NOTES: Subscripts 1 and 2 refer to the two heights z_1 and z_2. In this study, $z_1 = 1m$ and $z_2 = 2m$ were used. Differences of c, e, U, and T measured between z_1 and z_2 are indicated in terms of the respective gradients (or finite differences) Δc, Δe, ΔU and ΔT. PML model is based on Pruitt, et al. (1973). B-D model is based on Businger (1966), Dyer (unpublished), Dyer and Hicks (1970) and Webb (1970).

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