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THE ENERGY BUDGET AT THE EARTH'S SURFACE: ASSESSING SOURCES AND SINKS OF CARBON DIOXIDE IN A CORN CROP USING A MOMENTUM BALANCE APPROACH

Contribution by:

E. R. Lemon and J. L. Wright

INTERIM REPORT

E. R. Lemon - Investigations Leader

July 1967

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UNITED STATES ARMY ELECTRONICS COMMAND

Atmospheric Sciences Laboratory, Research Division
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Ithaca, New York 14850

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Prepared by

E. R. Lemon and J. L. Wright

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ASSESSING SOURCES AND SINKS OF CARBON DIOXIDE IN A CORN CROP USING A MOMENTUM BALANCE APPROACH

E. R. Lemon and J. L. Wright

INTRODUCTION

In two previous communications (Wright and Lemon 1966a, 1966b) an aerodynamic method was described for evaluating the source and sink distribution of carbon dioxide in plant communities. Some data were presented for a corn crop, giving quantitative information about photosynthetic fixation and respiration release of carbon dioxide, layer by layer, within the crop.

In the method, CO_2 concentration profiles and windspeed measurements of the bulk air were made within and above the crop. The analysis of the windspeed measurements to calculate diffusivity coefficients required tedious analysis of windspeed fluctuations and the application of complicated statistical and mixing length theories. It is our purpose to present here a simpler method, requiring vertical profiles of mean windspeed, vertical profiles of mean carbon dioxide concentration and representative vertical profiles of the foliage surface area density of the plant community.

THEORY

If one knows the vertical flux intensities of the CO_2 diffusion streams across two horizontal planes within a plant community, the difference between the two intensities provides knowledge of the source strength (respiration) or sink strength (photosynthesis) of the layer of foliage between the two planes. The vertical flux intensity of CO_2 across each plane at height z above the ground is given by

$$P = K_c \, dC/dz \qquad [1]$$

where P is the flux intensity taken to be positive downwards in $g/cm^2/sec$, K_c is the CO_2 diffusivity coefficient in cm^2/sec, dC/dz is the CO_2 concentration gradient and C is the CO_2 density in the air in g/cm^3. The gradient dC/dz is obtained by taking the slope of a mean CO_2 concentration profile at the specified height z. It is in the evaluation of K_c wherein the difference lies between the previous reported method and the one reported here. The simpler one is called a momentum balance.

Momentum is extracted out of the wind stream by plant surfaces. This is evident since air has mass and the wind velocity is slowed to zero as the ground is approached. Leaf-waving and stalk-bending are manifestations of the frictional drag of the wind on foliage surfaces. The flux intensity of the vertical exchange of horizontal momentum out of the wind stream is defined by a diffusion-like equation similar to the one for CO_2:

$$\tau = \rho K_m du/dz \qquad [2]$$

where τ is the flux intensity of momentum exchange at some plane z in dynes/cm^2; ρ is the density of the air (0.00118 g/cm^3 at 25 C and 1013 mb); K_m is the diffusivity coefficient for momentum in cm^2/sec; du/dz is the windspeed gradient or the slope of the mean windspeed profile at level z; and u is the mean horizontal wind velocity in cm^2/sec.

In the application of the momentum balance method one assumes that K_m = Kc, while K_m is determined from Equation [2] by evaluating τ and du/dz at the appropriate level of z.

For this, two measurements are required in the field; the distribution of foliage surface area of the plant community as a function of height and the mean windspeed profile for say 10 to 20 minutes, extending from the ground to well above the plant community. Figure 1 schematically illustrates a generalized mean windspeed profile and a foliage area density profile. The figure also illustrates the method of evaluating τ_z at a specific level z. First, an evaluation of τ_h at the top of the vegetation (which is the total flux intensity of momentum) is made from an analysis of the log distribution of the wind velocity above the vegetation by

$$\tau_h = \rho \left[\frac{ku}{\ln (z - D)/z_o}\right]^2 \qquad [3]$$

where k is the von Karman constant (0.4), D is the community displacement parameter in cm and z_o is the roughness coefficient in cm. Second, τ_z is evaluated by "partitioning" the momentum with depth into the plant community to the specific level z by

$$\tau_z - \tau_o = \tau_h - \rho \int_z^h C_D F u^2 dz \qquad [4]$$

where C_D is the drag coefficient (dimensionless); F is the leaf or foliage area density, and h is the height of the community. The drag at the soil surface, τ_o, is considered to be negligible in dense plant communities, thus it is assumed that τ_o = 0.

The diffusivity coefficient is finally evaluated once knowing τ_z, by taking the slope du/dz of the mean windspeed profile at the specific height z and solving for K_m in Equation [2].

We shall take up the mechanics of evaluating the drag coefficient in Equation [4], C_D, as well as the other parameters, after giving the procedure for making the field measurements.

PROCEDURE

The necessary measurements were made on a clear day in a 20-acre cornfield on September 11, 1963 at Ellis Hollow (Ithaca), New York. The site used was that of the previous study (Wright and Lemon, 1966a and 1966b). The corn was planted in 29-inch north-south rows at a density of 26,000 plants per acre. The crop was a good one, having been well fertilized and amply supplied by favorable rains. All leaves were still green and evidently quite active photosynthetically despite the late date.

1. Wind measurements. The equipment for measuring the wind and the procedures for processing the data are identical to those reported earlier except that it is not necessary to perform the tedious analysis of the short-time fluctuations of the windspeed recordings. As mentioned earlier only the mean velocity profiles are required here. Briefly, the procedure consisted of measuring totalized cup revolutions over 10-minute test periods with cup anemometers (Thornthwaite Assoc.) placed above the crop at the following heights above the ground, 465, 385, 325 cm. The crop height, h, was 285 cm. Mean windspeed within the crop was determined by integrating over the same 10-minute test periods the continuous recorder traces obtained from the outputs of heated thermocouple anemometers (Hastings-Raydist) placed at the following levels above the ground, 325, 275, 225, 175, 125, 75 cm.

2. Sampling procedure for CO_2. In the estimation of carbon dioxide exchange rates reported here many improvements have been made over the sampling and analytical methods reported earlier. In the earliest work (Lemon, 1960), carbon dioxide profiles were obtained above the crop by simultaneously sampling the air above the plants at several levels using single hose openings as point sinks at each level. No attempt was made to obtain horizontal spacially integrated samples even though the samples were time integrated. In more recent work concerning CO_2 profiles within the vegetated canopy of a corn crop (Wright and Lemon, 1966b) a spacially integrated sampling procedure was used. In their study, however, air samples were taken in time sequence at the several levels above the ground and not simultaneously. Thus the samples may have been non-representative due to time fluctuations in carbon dioxide concentration but not to spacial fluctuations in carbon dioxide. This error was minimized, nonetheless, by the fact that the sampling time was; a) relatively long (ten minutes) compared to the usual 1/3 to 1/2 cycles per minute short time CO_2 concentration fluctuations commonly experienced in our cornfield studies, and b) relatively short compared to the diurnal fluctuations in CO_2 concentrations. In order to avoid these previous possible sampling errors due to the time and space fluctuations in CO_2, the following sampling procedure was developed.

A series of perforated sampling hoses suspended horizontally and connected to the suction side of individual air pumps provided the means of spacially sampling the air at the various desired levels within and above the crop canopy. Continuous and simultaneous subsampling from the exhaust side of each pump into storage in 24-liter PVC beach balls provided a time integration over the 10-minute sampling periods.

Common PVC garden hose of 2 cm ID was used both for sampling and lead-hoses. A 7.5 meter section of hose with 0.1 cm diameter holes drilled every 15 cm acted as the horizontal spacial sampler at a given level, each being connected to a 30-meter lead-in hose running downwind to an instrument trailer where the pumps and analytical equipment were located. The 7.5 meter sampling hoses were suspended on a wire frame at right angles to the corn rows and prevailing wind. They were located at the following levels above the ground: 35, 95, 135, 165, 190, 225, 250, 280 and 310 cm. The 225 cm sampling hose was positioned immediately above the upper large leaves of the canopy with topmost smaller leaves and corn tassels extending about another 50-60 cm above.

Experience has proven that a relatively high lead-in air flow rate is important when using plastic tubing because of diffusion of CO_2 through the tubing walls if the lead-in is permitted to lie on the ground. Also the inevitable slow evolution of organic gases out of the hose wells contaminates the sample air to a serious degree if flow rates are too low and/or lead-in too long. Fortunately, PVC garden hose is convenient, inexpensive, relatively impervious to CO_2, and of sufficient diameter to easily incorporate an internal heater wire to prevent water vapor condensation, all in addition to permitting acceptable airflow rates with proper pumps. (We have found, however, that mice chew heated PVC hose during the cool seasons.) The lead-in hoses were connected to suction pumps each having a capacity of delivering 28 liters per minute. Thus satisfactory sample air can be continuously delivered with little delay.

Mention has been made of preventing water vapor condensation in sample and lead-in hoses with internal heater wires. Two reasons are emphasized; a) condensed water absorbs and evolves CO_2, imparting historical effects on any given sample, and b) differential evaporation or condensation of water in the sampling hoses create wide difference in water vapor content in the air samples. This causes serious analytical problems when using infrared analysis for CO_2. The fact is, that it is impossible for most commercial infrared CO_2 analyzers commonly used to completely discriminate between water vapor and CO_2. Thus water vapor acts, to some degree as CO_2, giving an erroneously high measurement for CO_2. For studies of the sort reported here where small CO_2 gradients are measured, water vapor errors have to be reckoned with. Two alternatives are open, either remove the water vapor from the sample air before analysis or correct the measurements by knowing both instrument discrimination characteristics and water vapor content of the sample. In these studies the former was employed by absorbing the water vapor in magnesium perchlorate before the sample air passed into the storage balloons. Magnesium perchlorate is a preferred absorber. (The same cannot be said for silica gel because it imparts historical effects through absorption and evolution of CO_2 to a given sample of air.) (See Tamm, E. and Krzysch, G., 1959.)

3. Analytical procedure for CO_2. Since there were only six pumps available and nine sampling levels, cyclic sampling and analytical procedures were used. That is, six sampling levels, i.e. 35, 95, 135, 165, 190 and 225 cm were first sampled simultaneously, the air being stored in six balloons then subsequently analyzed. During the analysis of these first six samples a second series of six levels, i.e. 165, 190, 225, 250, 280 and 310 cm were sampled, filling a second series of six balloons to be subsequently analyzed. It was found convenient to make simultaneous wind and carbon dioxide runs of 10-minute periods twice each hour. Thus each series of six sampling levels for CO_2 was sampled once each hour and each series was sampled roughly 30 minutes apart.

Upon filling a given series of six balloons, analyses immediately began. This consisted of attaching two balloons to individual aquarium pumps which were matched to give equal flow rates into the two cells of the infrared analyzer. Flow rates were continuously monitored and adjusted to deliver air at one liter per minute. The outlets of the two cells of the analyzer were to ambient atmospheric pressure. The air that was sampled at the 225 cm level was used as reference, thus the 225 cm balloon filled each given series provided reference air to the "reference" cell, while each of the other 5 sampling level balloons in a given series was analyzed in turn by connection to the "sample" cell. During the analysis of each of the 5 samples against reference, lead hoses from the aquarium pumps to the analyzer were reversed at least twice, in effect mechanically reversing sample and reference cells of the analyzer. This provided a check on each analysis and served to note any possible shift in instrument zero.

The instrument used for the differential analyses is a spacially designed unit, having a range of $\pm$ 12.5 ppm with a sensitivity of $\pm$ 0.2 ppm. Other details of the instrument are reported elsewhere (Wright and Lemon, 1966b). Calibration of this instrument and also another unit used to measure absolute concentrations of CO_2 was accomplished with commercially available standard gases. Experience has shown that both instruments become very stable after 2 or 3 weeks of continuous operation, requiring only occasional check on calibration span and zero.

During the period of experiment reported here, air from the 225 cm level was continuously monitored for absolute concentrations of carbon dioxide. This enabled the expression of all profiles on an absolute basis.

Since the present study concerns the vertical distribution of activity within the canopy, emphasis is given to those series of samplings that provide complete profiles within the canopy. Inspection of Figure 2 reveals, however, the inclusion of one profile above the canopy purely for interest. One can also notice that experimental points have been plotted at the 310 cm level for many of the "within canopy profiles." These 310 cm points are to be viewed with caution, however, since they were obtained 30 minutes following the indicated time when the "within canopy" profiles were taken. Invariably the "above canopy" 310 cm point fell to the right of the extrapolated profile line in the morning and to the left in the afternoon as one would predict. They are only included here as a guide and do not affect the "within canopy" profiles or subsequent calculations.

4. Leaf area density measurements. The surface area of leaves and stalks in 50 cm height increments was measured on each of twenty representative individual plants giving a total of 20 area measurements for each of five height increments. The surface area of stalk and tassel in the 6th or uppermost height increment was also estimated. The 20 plants chosen for area measurements were individually selected on the basis of height and stem diameter, being "mean" or "standard" plants chosen out of the large population. The leaf area was determined on a one-side basis by measuring length and width and multiplying by the factor 0.75 and estimating what part of each leaf fell within the specific 50 cm increments. Stalk area was estimated from stem diameters and treating them as cylinders.

Knowing the mean leaf area (one side) and mean stem area per plant within each 50 cm increment we plotted the sum of these for each increment on a cumulative basis from the top of the crop downwards. A smooth curve was then constructed through the points. From this cumulative curve and the population density it was possible to construct a representative foliage area density profile as found in Figures 3 and 4.

5. Data analysis. Experience has indicated that more representative wind profiles can be obtained by combining numerous short-time profiles. For this reason all the wind profiles taken during the day were combined in a normalizing procedure. Figure 4 presents the mean normalized procedure.

A systematic computer analysis of several hundred log wind profiles taken throughout the growing seaon in 1961 over a similar corn crop at the Ellis Hollow site provides us with good representative values for the log profile wind parameters required in Equation [3]. The plant community displacement parameter D, turns out to be 140 cm and the roughness coefficient z_o is 15 cm. Experience has also indicated that Equation [3] does not have to be corrected for non-isothermal conditions when soil moisture is plentiful.

We now need to return to the problem of determining the diffusivity coefficient K_m, from the momentum balance. We have made the assumption that all of the momentum extracted from the wind stream is related to the foliage area and that the soil surface plays a negligible role in dense vegetation. Thus the total momentum or shear, τ_h, can be defined by:

$$\tau_h = \int_0^h \rho \, C_D \, F \, u^2 \, dz. \qquad [5]$$

Now we have to make another assumption. In order to provide an estimation of the drag coefficient, C_D, we have to assume that it is a constant, independent of depth into the vegetation and independent of windspeed. It can be evaluated from

$$C_D = \frac{\tau_h/\rho}{\int_0^h F \, u^2 \, dz} \qquad [6]$$

if one knows the total drag τ_h, the leaf area density, F, distribution with height and the mean windspeed, u, distribution with height. C_D is thus a mean drag coefficient for whole crop. It is truly a plant community physical parameter, characterizing the community's ability to extract momentum out of the air stream.

It was mentioned earlier that the total drag τ_h is evaluated from Equation [3]. The integration required in the denominator of Equation [6] can be graphically performed by determining the area under the curve constructed from the product of F u^2 in its distribution in height from z = 0 to z = h. Figure 3 gives the results; it really represents the distribution of drag in the corn crop.

Through successive analysis of many levels of z, now having evaluated C_D, a vertical distribution of momentum flux intensities, τ_z, can be evaluated from Equation [4]. In turn, vertical profiles of the diffusivity coefficient, K_m, can be constructed from Equation [2] or

$$K_m = \frac{\tau_z/\rho}{du/dz} = \frac{(\tau_h/\rho) - C_D \int_z^h F\, u^2\, dz}{du/dz} \qquad [7]$$

Figure 5 presents the mean normalized profile of the diffusivity coefficient distribution with height for the day. The absolute values at the top of the community ($K_z/K_h = 1.0$) are given for the specific hours of the day in tabular form in the figure. It should be pointed out that these values are five orders of magnitude larger than molecular diffusivity values in air. Even near the base of the corn crop the values are three orders greater than molecular values. Thus turbulence must be the chief means of gaseous transfer even at the base of plant communities. It should also be pointed out that attenuation of diffusivity with depth into the canopy is almost linear to more than half way to the ground on a semi-log plot.

With the assumption that $K_m = K_c$ we are now ready to utilize gradients, dC/dz, from the CO_2 profiles in Figure 2, to calculate CO_2 flux intensities, P, of several levels of z from Equation [1]. The results are presented in Figure 6.

Figure 6 presents the quantitative strength of the upward and downward diffusion streams of carbon dioxide. Positive values on the left-hand side of the figure indicate downward diffusion. Negative values indicate upward diffusion on the right of the zero axis. It can be noted here that there was very little CO_2 coming from the soil. Returning to Figure 2 it can be seen that there was very little increase in CO_2 as the soil is approached. More sampling points very near the soil surface are needed, however, to clarify this point. In any event an increase in CO_2 upward flux intensity coming up into the canopy is evidence that the lower portion of the canopy was respiring. At the level where there is neither a decrease or increase in upward flux, depending upon the hour of the day, the leaves were at the light compensation point at this position of the canopy. Above this level the upward flux decreases, since photosynthesis is taking CO_2 out of the air. A level is soon reached where no longer is the CO_2 diffusing upward but necessarily CO_2 is diffusing downward from the atmosphere. It is rather interesting to realize that the CO_2 that is respired from the ground and the lower portions of a canopy may be reabsorbed in the upper photosynthesizing portions during the day. The 1755 hour profile indicates that reabsorption was not quite complete since there was an upward flux throughout the whole profile.

By taking the slopes of the profiles in Figure 6 one can construct flux divergence profiles or source and sink profiles of carbon dioxide. Figure 7 presents some representative profiles of this nature. The left-hand side of the axis represents the rate at which CO_2 is being absorbed in photosynthesis in a unit volume of canopy space. On the right of zero is the quntitative rate that CO_2 is being generated through respiration in a unit volume of canopy space. The qualitative discussion of the curves in Figure 6 is now made clear on a quantitative basis in Figure 7 insofar as defining the levels of photosynthesis and respiration. The light compensation point is the zero axis profile intercept in this figure. Maximum respiration is apparently near corn ear level, while maximum photosynthesis is near maximum leaf area density.

A much deeper analysis of these last profiles is possible by referring to the radiation studies made simultaneously in the same field by Allen and Brown (1965). They made a careful study of the mean radiation distribution in the canopy in the 0.3 to 0.7μ wave length interval (visible or "photosynthetically active" radiation). From their work one is able to obtain both radiation flux intensities and flux divergence (absorbed light) distributions with height in the canopy. From the later, photoefficiency curves can be constructed knowing both the flux divergence for CO_2 and flux divergence for light. Two midday representative efficiency curves are presented in Figure 8. Both bracket local noon (1210 EST) about equally. On the basis of absorbed visible radiation, the maximum efficiency of the canopy falls between 12% and 18% in the region of maximum leaf area density. Efficiency drops off both above and below this region. Speculation about unfavorable water relation in the top portion of the community during the afternoon might give explanation to the lower efficiency of the upper portions of the 1358 curve compared to the 0955 curve.

As for further differences between the two curves let us now look at some light intensity response curves. These are plotted in Figure 9. Here are plotted CO_2 exchange rates (and energy equivalence) on a leaf area basis as a function of light intensity (radiation flux intensity in the 0.3 to 0.7 wave length interval). Each point plotted respresents a different leaf level for the hour specified beginning with the top leaf level of 225 cm at the maximum radiation for that hour and proceeding downwards in 25 cm increments with decreasing light intensity. Not all the lower points are plotted for the 0755 and 1755 hours. There are several interesting observations to be made: a) apparently all leaves at any given hour follow the same light response curve no matter their position in the canopy, at least above the compensation point. b) the light response curves are remarkably linear. This is not too different from some light response curves of individual leaves in corn or sugar cane. c) the light compensation point is directly related in some way to the level of total photosynthetic activity of the canopy. d) the respiration rate is very low and curiously becomes rather constant once the compensation point is reached. It appears to be rather insensitive to temperature since the temperature ranged from: 14°C at 0755; 19°C at 0955; 23°C at 1358; and 19°C at 1755 hours.

Turning back to the differences noted in Figure 8, it can be seen in Figure 9 that the light response curves for both the 0955 and 1358 hours are alike except for the upper two or three leaf levels at the top of the canopy. As mentioned above, the 1358 upper leaves might have been under water stress. Evidently the gross differences in the two curves in Figure 8 can be fully explained on the basis of a greater radiation flux at 1358. The incident visible radiation flux intensity at the top of the crop was 0.51 $cal/cm^2/min$ at 1358 and 0.45 $cal/cm^2/min$ at 0955.

On the basis of visible light intensity, the slope of the 0955 and 1358 curves in Figure 9 yields a photo-efficiency of 7.3%. The other two yield efficiencies greater than 25% during periods of low radiation.

In summary, it should be pointed out that despite the assumptions required in the momentum balance, the end results seem quite reasonable. This may be blind luck in the choice of corn. Several reasons can be given as to why corn might be a lucky choice: 1) first and foremost, corn is a relatively open and uniform system. (Several subsequent points arise from these conditions.) 2) Open structure prevents development of large gradients in the climatic elements. These include light, wind, temperature, water vapor and carbon dioxide. Thus corn leaves in different portions of the canopy are not exposed to as wide a variation in climate as leaves in a compact system such as clover. This prevents, for example, wide respiration differences due to wide temperature difference. This also prevents disease due to wide variation in humidity. 3) Good wind flow characteristics in corn may favor a high Reynolds number, so that the assumption of constant drag coefficient is more realistic than in a compact system. 4) Forced convection in an open system makes more realistic the assumption that $K_m = K_c$ where "free" convection is probably not as important to diffusion as in a compact system.

Probably the energy balance method of determining the diffusivity coefficient is more correct in compact communities, while the momentum balance method is more applicable to open canopies under good wind conditions.

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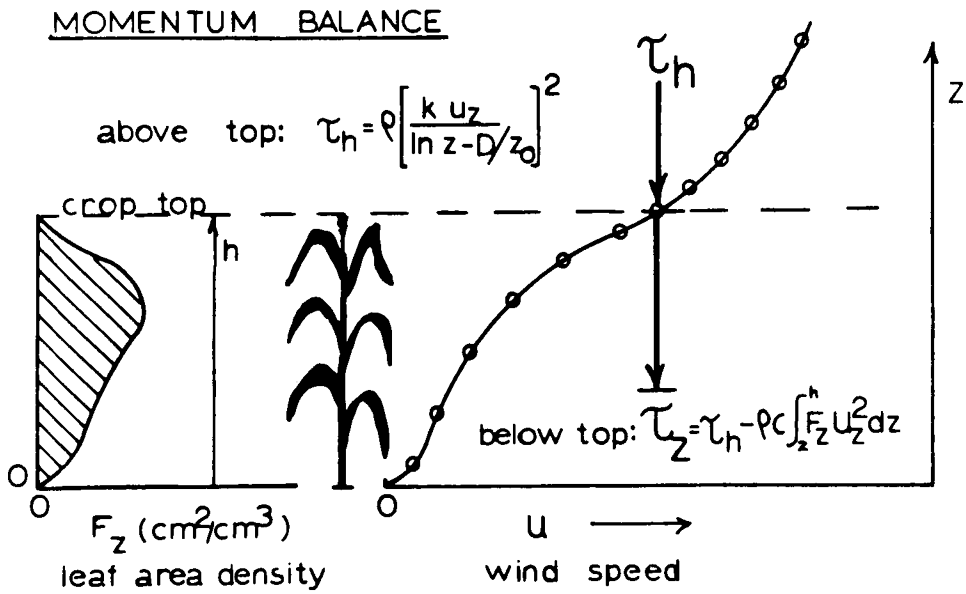

Fig. 1. Schematic representation of momentum balance component measurements in a plant community. Profiles of leaf surface density (F) and mean wind velocity ($\bar{u}$) are illustrated. Total drag at the top of the community is indicated by (τ_h) and drag of the canopy layer from z to h is indicated by (τ_z) at level z. The drag coefficient is defined as (C). Other symbols are as found in the text.

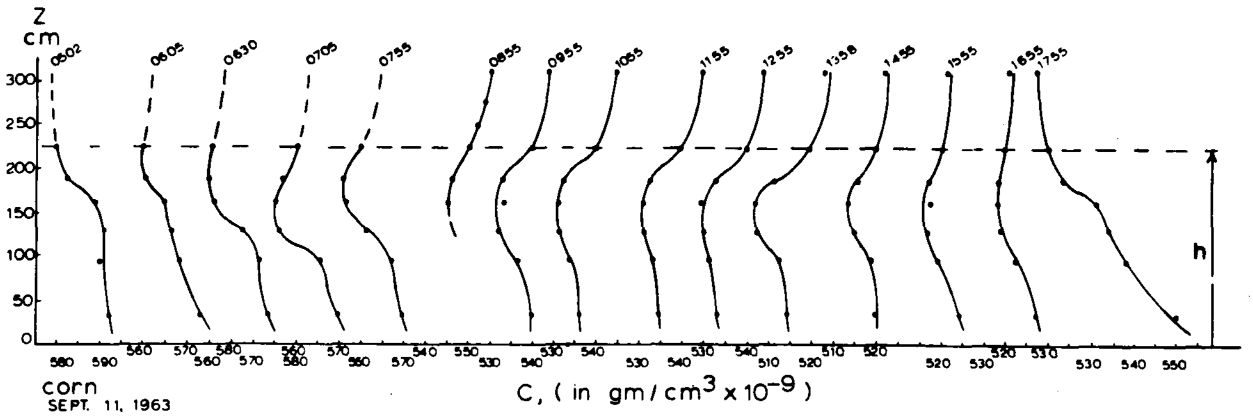

Fig. 2. Carbon dioxide concentration, ($\bar{C}$), profiles in a corn crop of height h. Time of measurement is indicated at the top of each profile. Experimental points are relative for a given profile only. Absolute values are indicated but each curve is displaced for clarity. Ellis Hollow, N. Y.

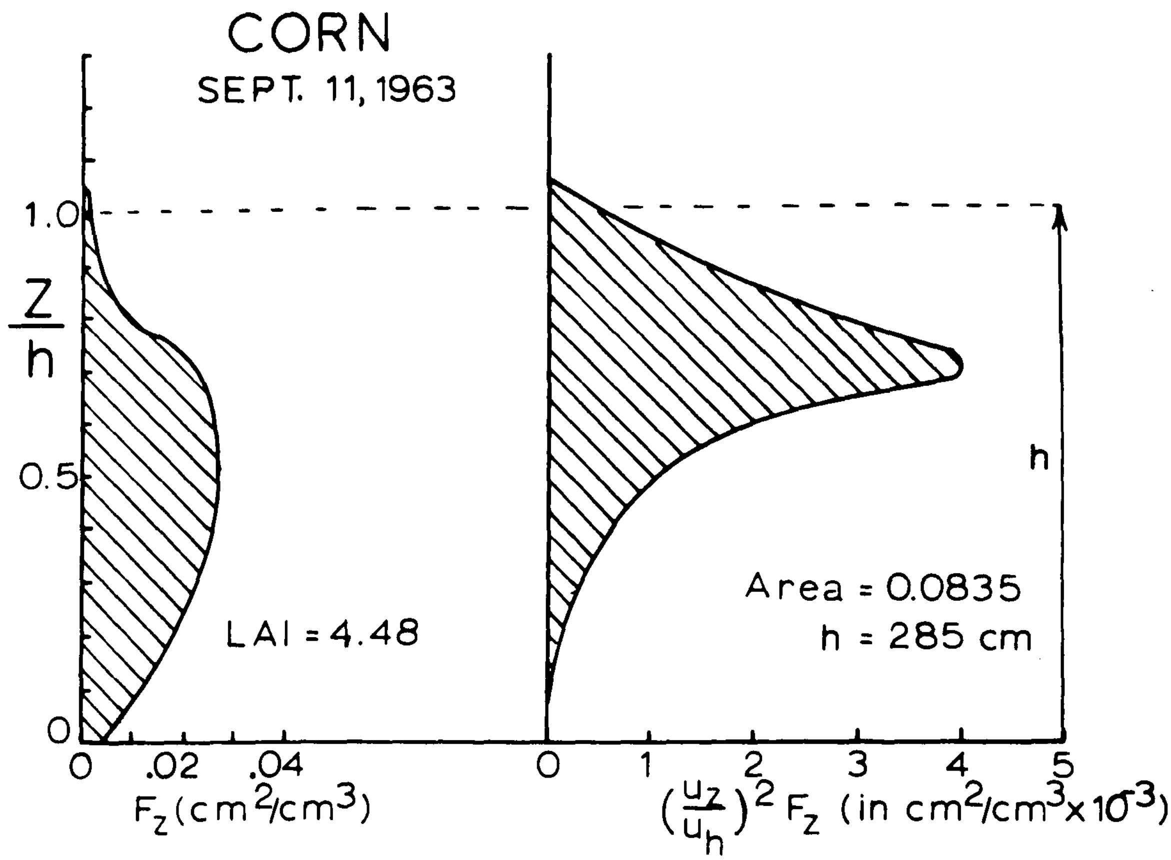

Fig. 3. Leaf area density profile (F_z) and drag distribution ($(u_z/u_h)^2 F_z$) in a cornfield. Ellis Hollow, N. Y.

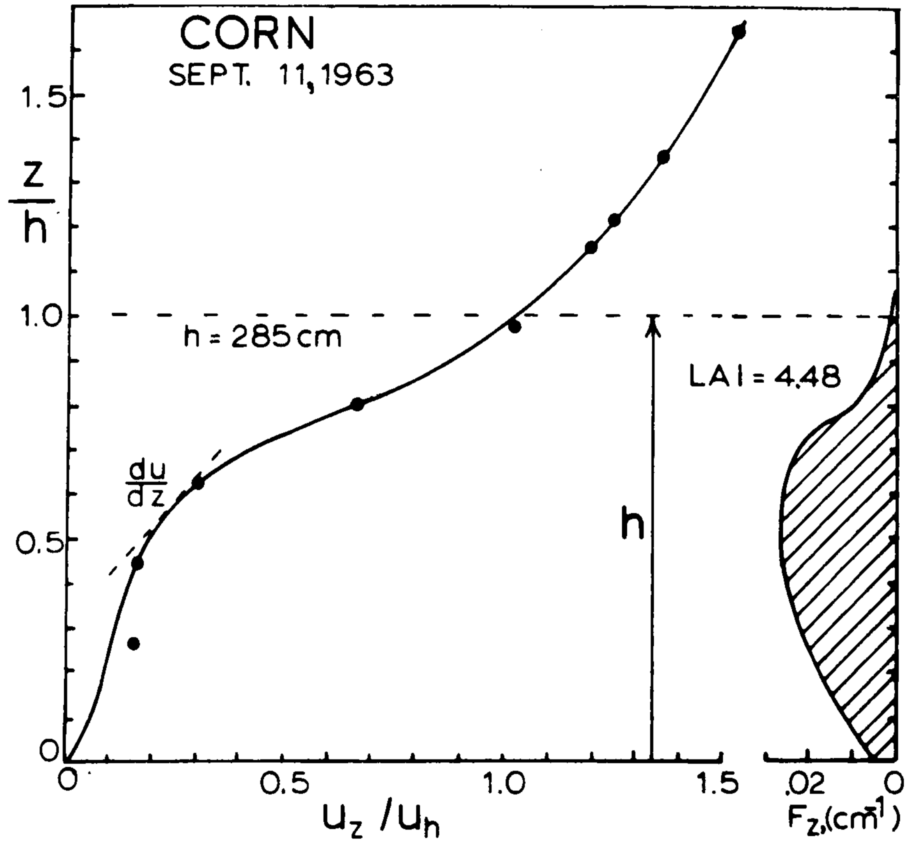

Fig. 4. Leaf area density profile (F_z) and mean wind velocity ($\bar{u}$) profile in a cornfield. Wind velocity profile is normalized and represents a mean of all profiles taken during the day, September 11, 1963, Ellis Hollow, N. Y. The slope of the profile at a given level z is indicated by du/dz and dashed line.

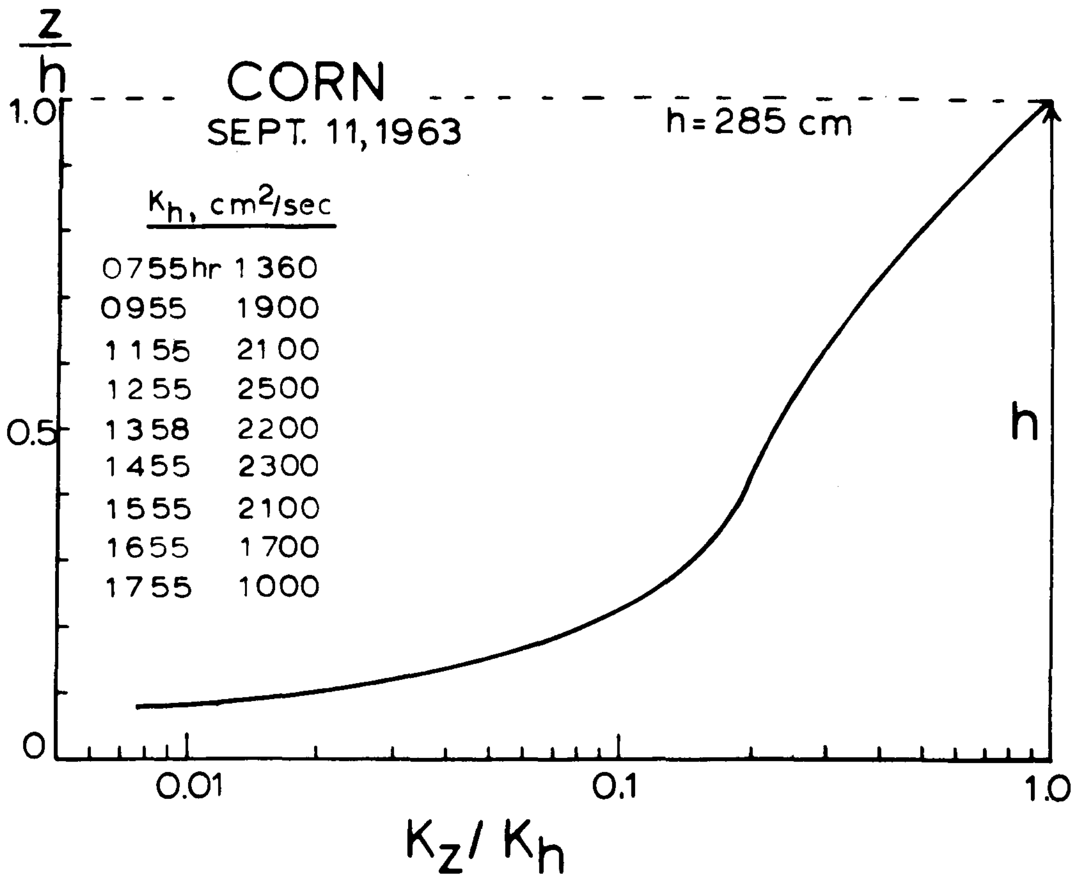

Fig. 5. Normalized profile of diffusivity coefficient (K_z) representing the mean of all profiles taken during the day in a cornfield, Ellis Hollow, N. Y.

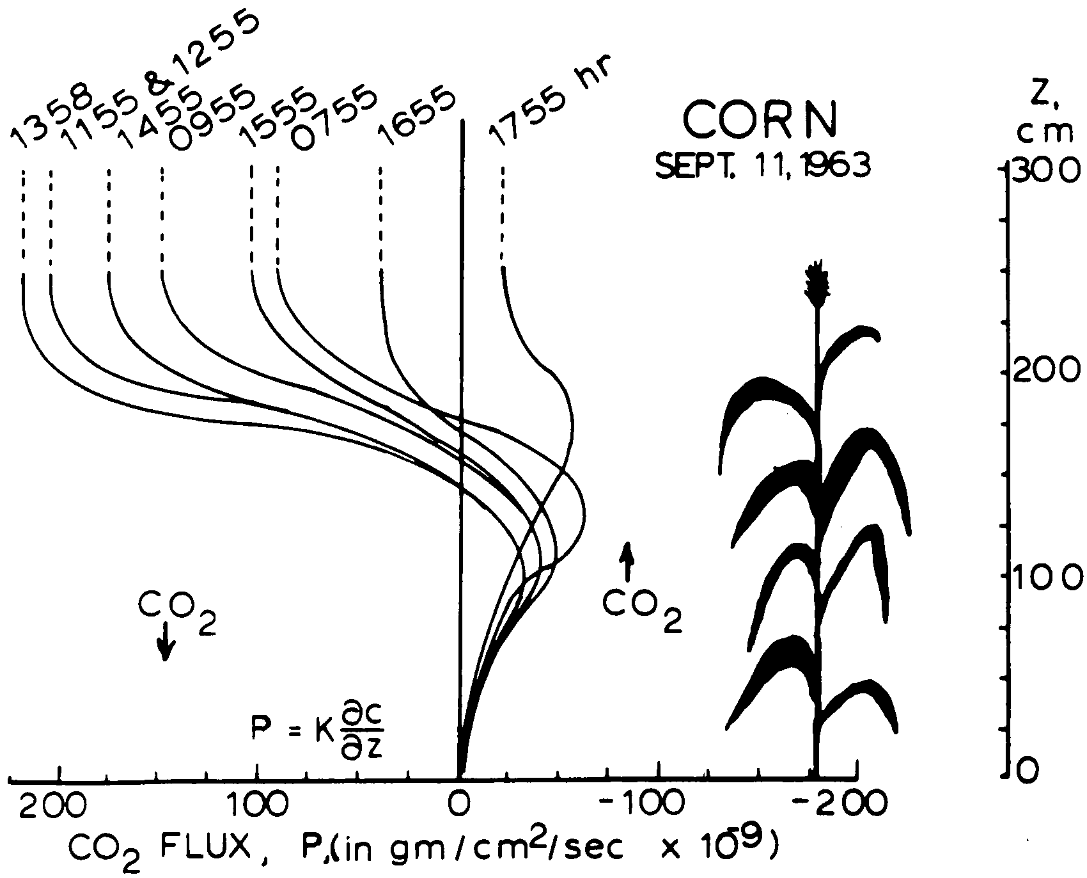

Fig. 6. CO_2 flux (P) profiles in a cornfield as indicated by hour at the top of each profile. Negative flux indicates CO_2 movement upward and positive flux indicates CO_2 downward movement. Ellis Hollow, N. Y.

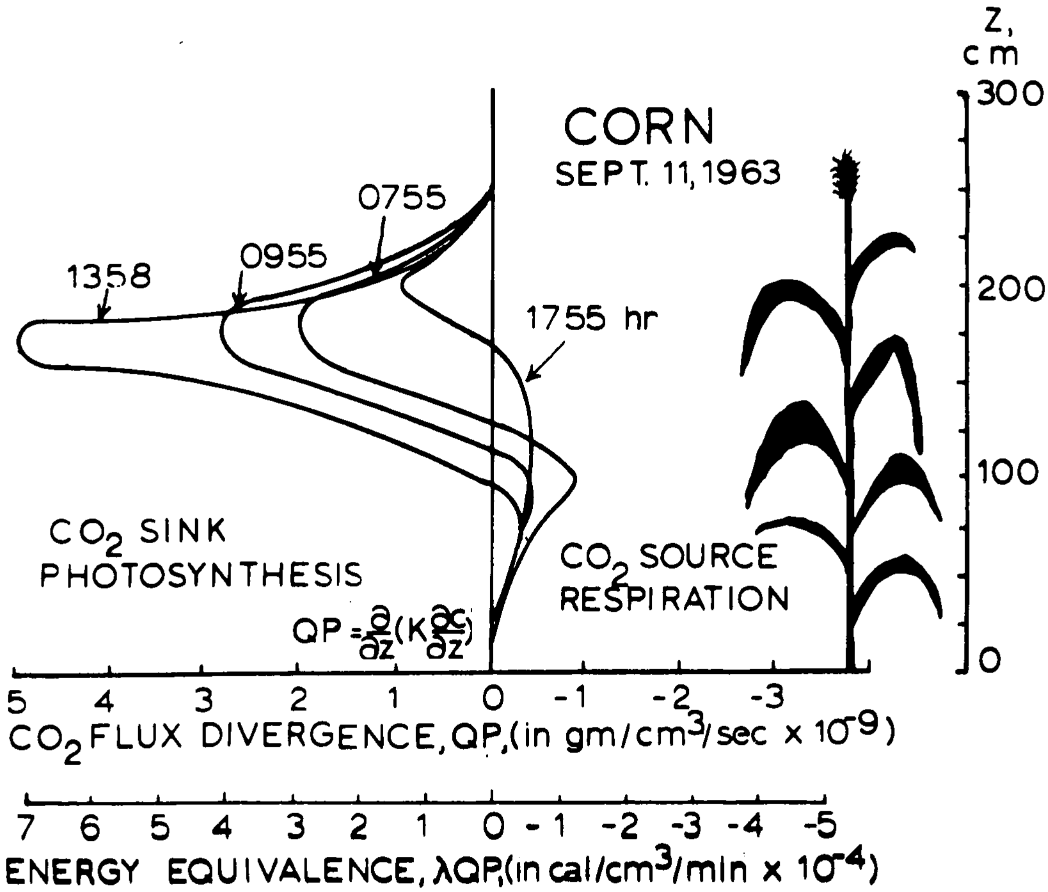

Fig. 7. Source and sink intensity distribution of CO_2 (QP) and photochemical energy (λQP) for indicated time in a corn crop. Negative values signify net respiration and positive values, net photosynthesis. Ellis Hollow, N. Y.

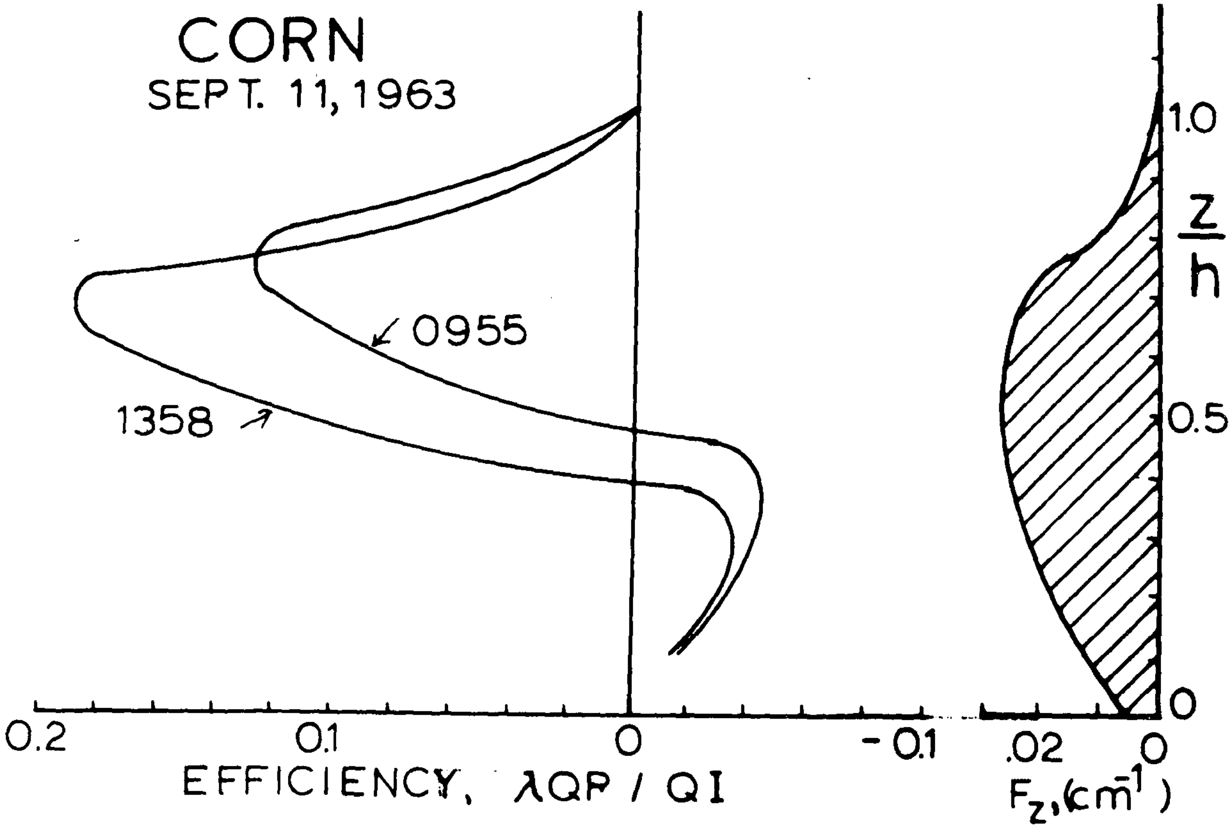

Fig. 8. Efficiency profiles (λQP/QI) of photochemical energy equivalence per unit of absorbed radiation (0.3–0.7μ wave length) in a cornfield at indicated hours. Leaf area density (F_z) profile presented for reference. Positive efficiency is for net photosynthesis and negative efficiency is for net respiration.

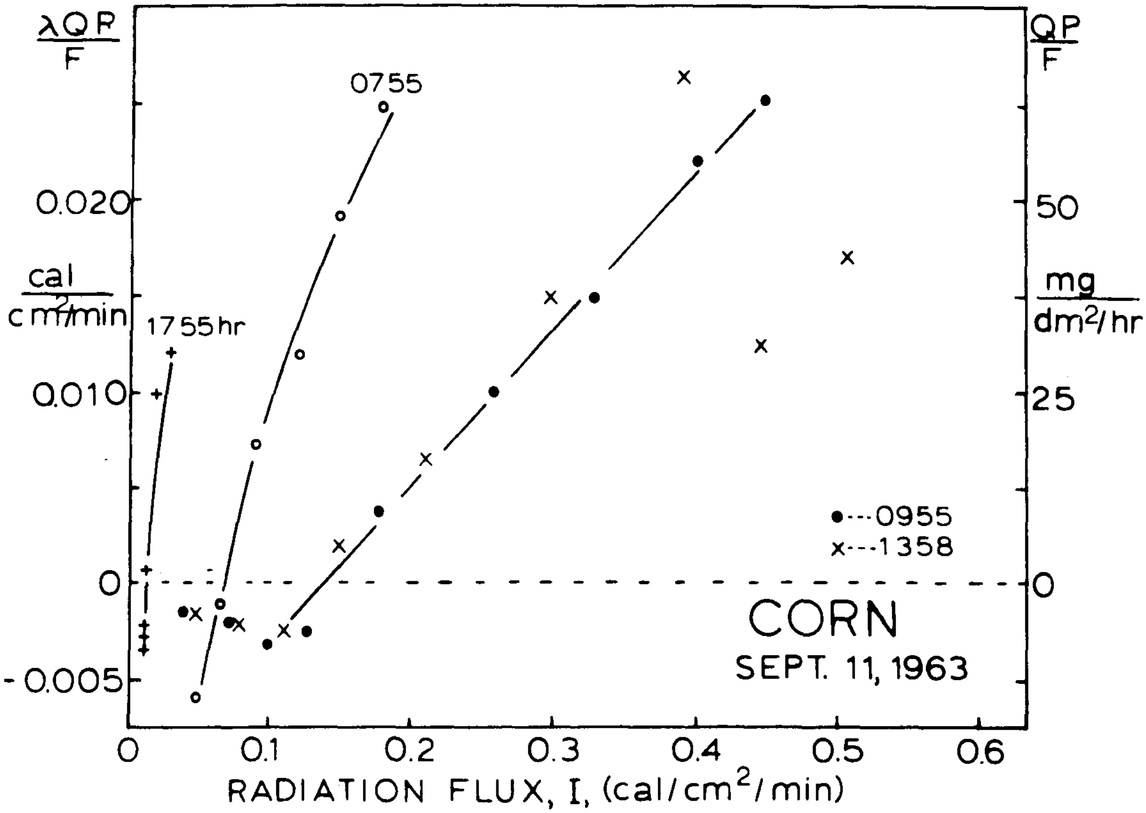

Fig. 9. Light response curves for corn plant community as indicated by hour. Radiation flux is incident intensity (0.3-0.7μ wave length). Photosynthesis and respiration expressed on a leaf area basis as CO_2 exchange or energy equivalence. Each point at a given hour represents a given leaf level in the canopy beginning with the top leaves at 225 cm at the highest radiation intensity and progressing downwards into the canopy in 25 cm increments with decreasing radiation. Not all 1755 and 0755 points near the bottom of the canopy are plotted. Each point is the "mean" response of all leaves at a given level. Ellis Hollow, N.Y.

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