# 4.1 DIURNAL CO$_2$ PROFILES FROM A *ZEA MAYS* L. CANOPY

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## 1. INTRODUCTION

Net canopy photosynthesis ($P_n$) has been defined by Brisco et al. (1975) as

$$P_n = \sum (P_a + R_s) - \sum (R_a - R_s) \qquad (1)$$

where $P_a$ is the photosynthesis attributed to CO$_2$ from the atmosphere, $R_a$ is sum of respiration from the soil ($R_s$), roots ($R_r$), and canopy ($R_c$). $P_a$ is greater than zero only during the daylight hours. $R_s$, $R_r$ and $R_a$ are greater than zero 24 hours a day. At an open-path infrared gas analyzer (IRGA) properly installed in the field, $P_a$ - $R_a$ is measured during the daylight hours, and includes any of the carbon from $R_s$ that escapes from the canopy. However in this instance, it is assumed that all $R_s$ during the daylight hours is fixed by canopy photosynthesis, and during the dark hours, assuming adequate mechanical mixing, $R_s$ is released into the atmosphere.

Observations of CO$_2$ fluxes from corn (*Zea mays* L.) canopies have been used to estimate the net ecosystem productivity (NEP) during a growing season. Comparisons of carbon fixation from an open path IRGA and periodic biomass sampling has revealed an underestimate of the carbon fixed as measured by the IRGA (Hollinger and Meyers, 2002). In earlier work Hollinger and Meyers (2002) showed that accumulating the mean 30-minute night $R_s$ with the daylight CO$_2$ accumulation obtained from the IRGA resulted in a reasonable estimate of NEP (Figure 1). $R_s$ was estimated using the mean dark hours $R_a$ measured by eddy covariance methods.

CO$_2$ profile measurements made in a canopy show an accumulation of CO$_2$ in the canopy during the night. During the daylight hours, CO$_2$ is depleted from the mid-canopy (Prueger et al. 2004). Near the soil surface the CO$_2$ concentration [CO$_2$] is greater than at mid-canopy. Such a profile suggests $R_s$ may be inferred from profile measurements of [CO$_2$].

The objective of this paper is to examine the contribution to NEP of $R_s$, measured with a CO$_2$ profile system located in a corn canopy.

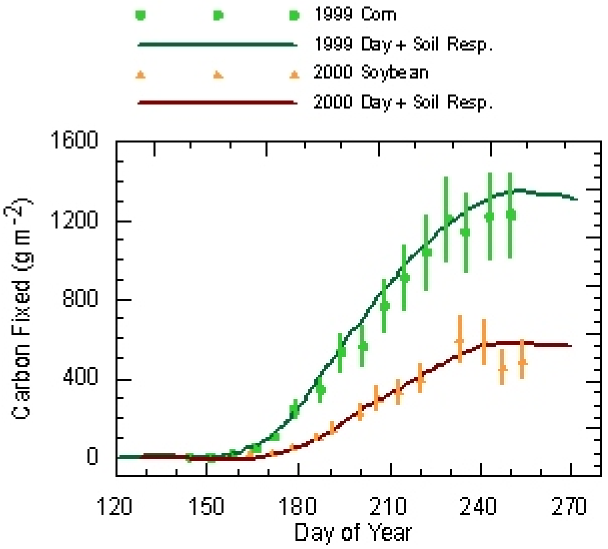

Figure1. Comparison between NEP estimated from biomass samples and eddy-covariance fluxes.

## 2. METHODS

CO$_2$ profiles were monitored in a no-till corn canopy, at the AmeriFlux tower located near Champaign, Illinois during the summer of 2003. The profile system consisted of a Li-Cor 820 CO$_2$ Analyzer** (LI-COR Incorporated, Lincoln, Nebraska), with four switchable ports, allowing for the monitoring of three levels, and one calibration port. The sampling lines were purged for 30 seconds before sampling began. Each night at midnight local standard time (LST) the gas analyzer was calibrated by purging the line of CO$_2$ and then a CO$_2$ standard was sampled. The three sample inlets were located at 0.05 m above the soil, at mid-canopy height, and at 10 m above the soil, the elevation of the open path IRGA on the AmeriFlux tower.

Measurements from AmeriFlux tower included CO$_2$ and H$_2$O$_v$ eddy covariance measurements, solar components (incoming and outgoing long and short wave radiation, net radiation, incoming and outgoing

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photosynthetic flux density), soil heat flux, surface temperature, air temperature and humidity, precipitation, soil moisture and temperature to depths of 1.0 m and 1.28 m, barometric pressure, and wind speed and direction. All variables were accumulated to 30 minute means.

Biomass measurements were collected once per week. These measurements included wet biomass of leaves, stems, sheaths, husks, cobs, and grain and leaf area index by two methods. The leaf area was measured optically with a LI-2000, and by manual measurement of the length and width of each leaf on three plants. Dry biomass for each of the plant compartments were obtained by drying the biomass samples in an oven at 50°C for two days. Three samples were collected from the field each week and the means and standard errors computed.

The $CO_2$ profile and AmeriFlux data were used to compute fluxes of $CO_2$ in the canopy. The flux from the 0.05 m level to the mid-canopy level was accumulated during the daylight hours to estimate the contribution of $R_s$ to canopy photosynthesis.

Fluxes from the $CO_2$ profile measurements were computed assuming a logarithmic wind profile above the canopy. Wind speed at the top of the canopy ($u_h$) was computed by

$$u_h = \frac{u^*}{0.4}\ln\left[\frac{h-d}{z_0}\right] \qquad \textbf{(2)}$$

where h is the height of the canopy, d the zero plane displacement, $Z_0$ the momentum roughness parameter, and u* the friction velocity. d was estimated using 0.65h and $Z_0$ was estimated as 0.1h (Campbell and Norman 1997). u* was determined using the momentum flux term (u'w') from the eddy covariance 3-dimensional sonic measurements. In the cases where u'w' was not available (2) was solved for u* using the mean wind speed at 10 m in place of $u_h$.

In the top 90 percent of the canopy, the wind speed was computed by (Campbell and Norman 1997)

$$u_z = u_h \exp\left[a\left(\frac{z}{h}-1\right)\right] \qquad \textbf{(3)}$$

where $u_z$ is the wind speed at height z in the canopy, $u_h$ is computed from (2) and a is the attenuation coefficient computed as

$$a = \left(\frac{0.2\,L_t h}{l_m}\right). \qquad \textbf{(4)}$$

In (4) $L_t$ is the total leaf area index of the canopy, and $l_m$ the mean distance between leaves in the canopy given by

$$l_m = \left(\frac{4wh}{\pi L_t}\right) \qquad \textbf{(5)}$$

and w is the mean width of the leaves (Campbell and Norman 1997) measured on a weekly basis.

The 0.05 m $CO_2$ profile inlet was in the lowest 10 percent of the canopy, a height below the level where (3) is applicable (Campbell and Norman 1997). Therefore, to compute the wind speed at 0.05 m, (2) was solved for u* with h replaced by $h_i$ which was equal 0.1h, d was assumed to be zero, and $z_0$ was assumed to be 0.01 m. Using the new computed u*, (2) was then used to compute the wind speed at 0.05 m.

The flux of $R_s$ to the mid-canopy was computed using K-theory (Campbell and Norman 1997), a log profile estimate, and an estimate from eddy fluxes during the night hours. The K-theory estimate is given by

$$C = -K_c \rho \frac{dC_c}{dz} \qquad \textbf{(6)}$$

where $K_c$, the $CO_2$ diffusivity, is equal to $0.15\sigma_w$ (Meyers and Paw U 1987). $\sigma_w$ is the standard deviation of the vertical wind velocity measured by the 3-dimensional sonic anemometer. The log profile flux estimates were computed using

$$\frac{E}{\sigma} = -\left(\frac{k}{\ln(0.05/z_m)}\right)^2 \left(\bar{u}_{0.05} - \bar{u}_m\right)\left(\bar{c}_{0.05} - \bar{c}_m\right) \qquad \textbf{(7)}$$

where the 0.05 subscript denotes the 0.05 m height of the lowest $CO_2$ profile inlet, m denotes the mid-canopy inlet height. $\bar{u}$ and $\bar{c}$ are the mean wind speed and [$CO_2$] at the two heights. The $R_s$ estimated from the eddy covariance measurements was the mean of all 30-minute night time $CO_2$ fluxes for the period from 20 June through 7 September.

## 3. RESULTS

Data were collected from the profile beginning on 20 June 2003 (day 171) and continued through the end of the year. For the period of 20 June through 7 September, the profile data show highest [$CO_2$] of the three levels near the middle of the canopy at 0330 LST (Table 1), and the lowest [$CO_2$] of the three levels near the mid-canopy height at 1330 LST. At sunrise (0600 LST) and sunset (1800 LST) a continuous gradient from the soil surface to the 10 m level is observed.

[$CO_2$] at the three profile levels for the period of 16 to 19 August (day 228 to 231) show an example of profile [$CO_2$] under different turbulent conditions (Figure 2). During the night of 16-17 August (day

Table 1. Mean $CO_2$ concentration (ppm) at three levels at time of maximum concentration at mid-canopy (1.2 m) height, sunrise, minimum concentration at mid-canopy, and sunset.

| | Time of Day (LST) | | | |
|---|---|---|---|---|
| Height | 0330 | Sunrise 0600 | 1330 | Sunset 1800 |
| 10 m | 440.0 | 438.9 | 360.5 | 363.3 |
| 1.2 m | 495.7 | 463.0 | 346.6 | 368.8 |
| 0.05 m | 502.1 | 474.5 | 358.2 | 390.1 |

228-229) the standard deviation of the vertical wind speed ($\sigma_w$) was less than 0.1 m $s^{-1}$ and there was a strong $CO_2$ gradient between the canopy and the atmosphere at 10 m (Figure 2a). The vertical line in figure 2 is at 0600 on 17 August and shows that the gradient was broken down in approximately two hours. Coincident with the breakdown of the gradient is a spike of $CO_2$ exiting the canopy as shown in the carbon flux trace (Figure 2b), an increase in the wind speed from <1 m $s^{-1}$ to approximately 2 m $s^{-1}$ (Figure 2c), and an increase in $\sigma_w$ from, <0.1 m $s^{-1}$ to approximately 0.4 m $s^{-1}$ (Figure 2d). On the following night (17-18 August, day 229-230), there is only a small increase in canopy [CO2] over that in the atmosphere at 10 m (Figure 2a). This night was characterized by wind speeds between 2 and 3 m $s^{-1}$ and $\sigma_w$ greater than 0.2 m $s^{-1}$. The carbon flux (Figure 2b) also shows a continuous efflux of carbon throughout the night, showing a coupling of the canopy with the atmosphere during the night of 17-18 August.

During the daylight hours, when carbon is being taken up by photosynthesis, the [$CO_2$] is lowest in the mid-canopy from approximately 0800 to 1600. Consistent with uptake of carbon from the atmosphere as seen by the carbon flux (Figure 2b). The lower [$CO_2$] at the mid-canopy compared to the 0.05 m level also indicates a contribution to photosynthesis from $R_s$.

The total contribution of $R_s$, including both soil and root respiration, was estimated by summing the day time estimates of the fluxes estimated from the K-theory, the log-profile method, and the night eddy covariance measurements. K-theory produced the largest rate of soil $CO_2$ fluxes (31.02 µmol $m^{-2}$ $s^{-1}$ during the day light hours, and 13.63 µmol $m^{-2}$ $s^{-1}$ during the night) and the eddy covariance measurements the smallest (3.97 µmol $m^{-2}$ $s^{-1}$). The log profile mean day flux was 10.69 µmol $m^{-2}$ $s^{-1}$ and at night 5.56 µmol $m^{-2}$ $s^{-1}$.

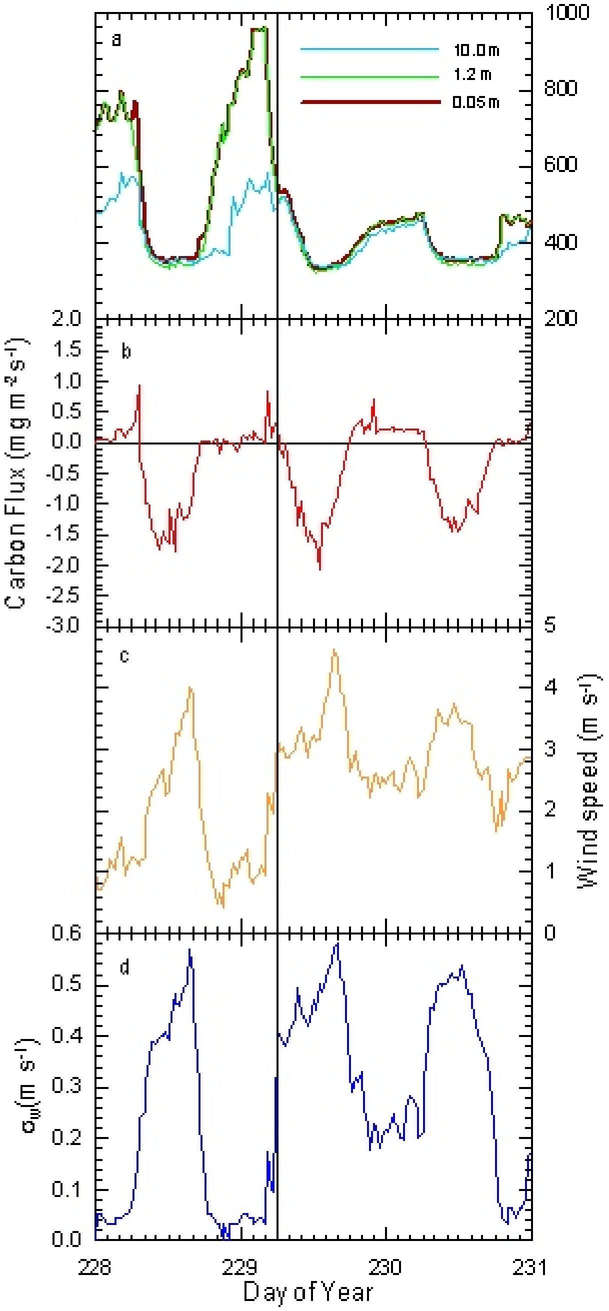

Figure 2. [$CO_2$] traces at two levels in the canopy and one in the atmosphere (a), carbon flux (b), wind speed (c), and the standard deviation of the vertical wind velocity ($\sigma_w$).

The 30 minute K-theory and log profile estimates of C accumulation attributed to $R_s$ were added to the corresponding 30-minute time period of C from the atmosphere. For the eddy flux estimates, the night time estimate of $R_s$ was added to the day light 30-minute flux measurements.

Even with gaps in the data, both the K-theory

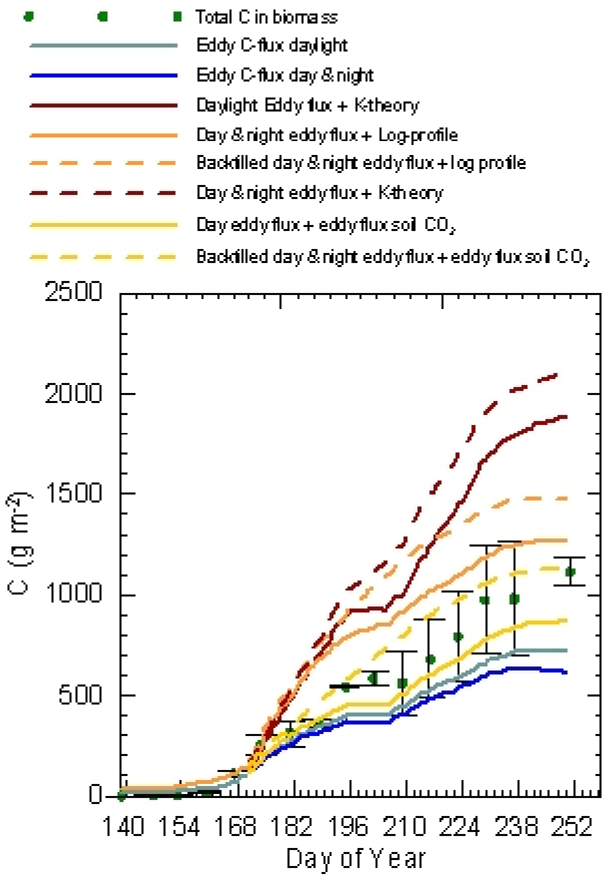

Figure 3. Carbon accumulation compared to weekly biomass measurements. The bars associated with the weekly biomass measurements are standard errors of the means.

and log profile overestimated the C assimilated by the canopy (Figure 3). Accumulating C from the observed C fluxes from eddy covariance, backfilling the gaps in the measurements, and including estimates of $R_s$ from the mean night $CO_2$ fluxes resulted in the best fit to the final biomass C estimate (Figure 3).

## 4. DISCUSSION

The $CO_2$ profile measurements clearly show an accumulation of $CO_2$ in the corn canopy during night hours. However, this accumulation does not occur every night. $CO_2$ accumulates on nights with little or no turbulent mixing characterized by $\sigma_w$ less than 0.1 m $s^{-1}$ and wind speeds less than 2 m $s^{-1}$. On these nights $[CO_2]$ as great as 1000 ppm may be observed. The fate of these high $[CO_2]$ is of interest, because if these concentrations were to persist into the daylight hours, photosynthesis rates would be stimulated. Comparing the profile concentrations to the eddy flux measurements and wind speed shows that these elevated concentrations are short lived in, and are generally flushed from, the canopy at sunrise. In fact, any time the 30-minute $\sigma_w$ exceeds 0.1 m $s^{-1}$ any accumulation of $CO_2$ is flushed from the canopy, and is detected by the open-path IRGA at 10 m above the surface. Therefore, we conclude that $CO_2$ released from the soil and canopy at night is not available for photosynthesis the next day.

On nights when $\sigma_w$ is greater than 0.1 m $s^{-1}$ $CO_2$ flux from the canopy is consistently measured at 10 m. On these nights there is a monotonic gradient from the surface to 10 m, with the highest concentrations occurring at the soil surface.

$[CO_2]$ are greatest at night (Table 1) at the three levels where measurements were made and begin to decrease at sunrise. By mid-day the middle of the canopy $[CO_2]$ are lower than the 0.05 and 10 m levels, producing a gradient between the 10 m and mid-canopy heights and between the 0.05 m and mid-canopy heights. These gradients support the hypothesis that the atmosphere and soil both contribute $CO_2$ to the photosynthesis process.

Previous work (Hollinger and Meyers 2002) showed that estimating the $R_s$ from the night eddy covariance measurements resulted in a reasonable estimate of the C accumulated in the biomass of both corn and soybean canopies. This work supports that earlier observation. Intuitively, use of the $CO_2$ profile measurements should have resulted in a better estimate. However, both estimates using the profile measurements fail to accurately estimate the $R_s$ contribution to canopy C. This failure is due to the application of the K-theory and log-profile methods to measurements and fluxes within a canopy. Both methods apply best to above canopy profiles. This initial analysis demonstrates the need to adapt models and procedures that work within canopies. In the interim, above canopy estimates of $R_s$ may be used to improve estimates of NPP.

## ACKNOWLEDGMENTS

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