# Relationship of Soil Respiration to Crop and Landscape in the Walnut Creek Watershed

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ABSTRACT

Soil respiration is an important component of the carbon dynamics of terrestrial ecosystems. Many factors exert controls on soil respiration, including temperature, soil water content, organic matter, soil texture, and plant root activity. This study was conducted to quantify soil respiration in the Walnut Creek watershed in central Iowa, and to investigate the factors controlling this process. Six agricultural fields were identified for this investigation: three of the fields were cropped with soybean [*Glycine max* (L.) Merr.] and three were cropped with corn (*Zea mays* L.). Within each field, soil respiration was measured at nine locations, with each location corresponding to one of three general landscape positions (summit, side slope, and depression). Soil respiration was measured using a portable vented chamber connected to an infrared gas analyzer. Soil samples were collected at each location for the measurement of soil water content, pH, texture, microbial biomass, and respiration potential. Field respiration rates did not show a significant landscape effect. However, there was a significant crop effect, with respiration from cornfields averaging 37.5 g $CO_2$ $m^{-2}$ $day^{-1}$ versus an average respiration of 13.1 g $CO_2$ $m^{-2}$ $day^{-1}$ in soybean fields. In contrast, laboratory measurements of soil respiration potential, which did not include plant roots, showed a significant landscape effect and an insignificant cropping system effect. Similar relationships were observed for soil organic C and microbial biomass. Additional analyses indicate that corn roots may be more important than soybean roots in their contribution to surface $CO_2$ flux, and that root respiration masked landscape effects on total soil respiration. Also, the failure to account for soil respiration may lead to biased estimates of net primary production measured by eddy covariance.

## 1. Introduction

Concern over global climate change has fostered an interest in documenting soil C sequestration in agricultural systems as a strategy to offset atmospheric $CO_2$ increases. This has resulted in a greater effort to understand the factors affecting soil C storage, as well as to assess soil C budgets (Lal et al. 1995). Carbon dioxide flux from the soil to the atmosphere is the primary mechanism of C loss from soils and a major component of terrestrial C budgets. Quantification of C losses, relative to inputs, may be a valuable technique for estimating the rate of change of soil C pools and for evaluating the impact of management practices on C sequestration in agricultural systems (Buyanovsky et al. 1985; Curtin et al. 2000; Duiker and Lal 2000; Paustian et al. 1997).

Micrometeorological methods such as the Bowen ratio and eddy covariance offer opportunities for the determination of annual net ecosystem exchange of $CO_2$. Within the past decade, several flux-monitoring networks have been established to assess net $CO_2$ exchange from terrestrial systems (Baldocchi et al. 2001; Svejcar et al. 1997). However, a major focus of previous work has been on forest and grassland systems, with relatively few measurements made on cropped systems.

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The fluxes measured by micrometeorological techniques can provide a direct estimate of the net ecosystem exchange of $CO_2$. It has been demonstrated that indirect estimates of gross primary production and ecosystem respiration can also be obtained (Falge et al. 2002). In studies of seasonal $CO_2$ flux from a variety of ecosystems, these investigators concluded that differences in the temporal patterns of assimilatory and respiratory processes is an important reason for characterizing these different components of net ecosystem exchange. Indeed, Falge et al. (2002) stated, "Hence these drivers (*temperature, moisture, light*) will affect net ecosystem carbon exchange ($F_{NEE}$) differently as they force $F_{GPP}$ (*gross primary production*) and $F_{RE}$ (*ecosystem respiration*) differently . . . Consequently, we need to understand primarily the factors that influence seasonality of the component fluxes, $F_{RE}$ and $F_{GPP}$, and govern the seasonal patterns of net fluxes" (italics added). Because ecosystem respiration is the sum of autotrophic and heterotrophic respiration, similar logic dictates that driving factors may differentially control the temporal dynamics of these two processes. This argues for detailed characterizations of these heterotrophic and autotrophic respiratory processes to provide a better understanding of the feedbacks on net ecosystem C exchange.

Respiration in terrestrial systems is the result of plant shoot respiration and soil respiration that includes both root respiration and heterotrophic respiration (micro- and macrofauna). Nighttime $CO_2$ fluxes that are quantified by micrometeorological techniques do not distinguish between above- and below-ground sources. Partitioning respiration between above- and below-ground sources may require a combination of techniques (Rochette et al. 1996). Soil chambers have been widely used to quantify $CO_2$ flux because of plant roots and the soil heterotrophic processes. Thus, soil chambers that are used in conjunction with micrometeorological methods may yield greater insights into temporal dynamics of $CO_2$ exchange, as argued for by Falge et al. (2002).

Estimation of cumulative $CO_2$ flux from the soil surface over the time periods that are required to evaluate agricultural management practices remains problematic. Temporal and spatial variability may often mask the differences in $CO_2$ flux arising from management changes (Duiker and Lal 2000; Hutchinson et al. 2000). The spatial variability of soil $CO_2$ flux has been characterized in several studies (Davidson et al. 2002; Rayment and Jarvis 2000; Rochette et al. 1991; Savage and Davidson 2003), where the coefficients of variation ranged from 25% to 85%. Despite these general reports of the magnitude of the spatial variability associated with soil respiration, there is little information on spatial variability in relation to landscape. Development of a more complete understanding of the factors controlling in situ soil respiration requires that the interactions associated with landscape position be assessed.

To provide additional insights into controls of soil respiration and to evaluate landscape influences, this study was conducted as part of the Soil Moisture Experiment 2002 (SMEX02) in the Walnut Creek watershed in central Iowa. The objectives of this experiment were to (i) characterize the factors controlling spatial variations of soil respiration, and (ii) relate soil $CO_2$ flux measurements to the net ecosystem $CO_2$ flux determined by eddy covariance.

## 2. Materials and methods

### *a. Site description and soil characteristics*

This study was conducted in the Walnut Creek watershed in central Iowa located 5 km south of Ames (41°75′N, 93°41′W) as part of the multiagency SMEX02 project (Kustas et al. 2003; Kustas et al. 2005). The Walnut Creek watershed is approximately 5100 ha in size and consists predominantly of privately owned land in corn/soybean production. The fields of this study ranged from 64 to 130 ha in size, and have been in 2-yr corn–soybean rotations since at least 1991. The typical tillage regime consists of fall chisel plow following corn, and spring disking of both corn- and soybean fields (Hatfield et al. 1999).

Soils within the Walnut Creek watershed were formed during the last glacial advance into Iowa during the late-Wisconsinan period between 14 000 and 12 000 yr ago (Hallberg and Kemmis 1986). The area is characterized by low-relief swell-and-swale topography, and surface drainage is inherently poor. As a result, subsurface drainage has been installed across much of the area. Numerous closed depressional areas, commonly called potholes, exist and have accumulated organic matter from surrounding side slopes. Soils are predominantly of the Clarion–Nicollet–Canisteo soil association. This association consists of well-drained Clarion soils, located on higher or sloping areas, somewhat poorly drained Nicollet soils, located on side slopes, Canisteo soils on poorly drained low areas, and very poorly drained Okoboji and Harps soils in the depressional areas. The soils that have been mapped are Canisteo silty clay loam [fine loamy, mixed (calcareous), mesic Typic Haplaquoll], Clarion loam (fine loamy, mixed, mesic Typic Hapludoll), Harps loam (fine loamy, mesic Typic Calciaquoll), Nicollet loam (fine loamy, mixed, mesic Aquic Hapludoll), and Okoboji

mucky silt loam (fine, montmorillonitic, mesic Cumulic Haplaquoll) (Soil Conservation Service 1981).

### b. Soil $CO_2$ flux

Soil $CO_2$ fluxes were measured in six fields within the Walnut Creek watershed during the period of 25 June–3 July 2002. Three of the fields were cropped with corn (WC06, WC13a, WC15) and three fields were cropped with soybeans (WC03, WC14, WC16). Field WC13a was not included in the overall SMEX02 sampling design, but was located directly east of, and adjacent to, field WC13. In each field a stratified sampling scheme was employed, whereby three replicate locations of each of the three general landscape elements were identified (summit, side slope, and depression), resulting in nine locations per field. At each landscape position within each field soil $CO_2$ flux, soil temperature (surface and 5 cm), and soil water content (surface, 6 cm) was measured at three separate locations located approximately 1 m apart. Soil water contents were performed using a soil moisture meter (model $TH_2O$, Dynamax, Houston, Texas).[1] An empirical algorithm was used to correct for the slight temperature effect on soil moisture probe response (Parkin and Kaspar 2003). Soil samples were also collected for laboratory analysis of soil microbial biomass, respiration, pH, organic C, and soil texture (described in section 2d, below).

Soil $CO_2$ fluxes were measured using vented chambers (27 cm diameter) placed on the soil surface (between plant rows) for 3 min. A polyethylene skirt that was attached to the outside of the chambers extended in a concentric ring approximately 30 cm out from the chamber wall and was held on the soil with a length of chain to seal the chambers at the soil surface (Denmead 1979). Headspace gas of the chambers was circulated through a portable infrared analyzer (model CI-301, CID, Inc., Vancouver, Washington) to quantify $CO_2$ concentrations. Carbon dioxide fluxes were calculated by performing linear regression on the $CO_2$ concentration versus time data or by the nonlinear procedure of Hutchinson and Mosier (1981). Each site was sampled only once during the 9-day period. To estimate daily soil respiration from these point-in-time measurements, the 5-cm soil temperature values were used, along with the average daily 5-cm soil temperature in a mathematical algorithm relating temperature and soil $CO_2$ flux [Eq. (1)]:

$$\text{daily average } CO_2 \text{ flux} = R_t \times Q^{(\mathrm{DAT}-T)/10}, \quad (1)$$

where $R_t$ is the measured $CO_2$ flux from a given soil chamber at time $t$, $T$ is the soil temperature at time $t$, DAT is the daily average temperature over the 9-day sampling period, $Q$ is the $Q_{10}$ factor, and daily average $CO_2$ flux is the resulting estimated daily average flux average based on the point-in-time chamber measurement (Parkin et al. 1996). For these corrections, a $Q_{10}$ factor of 1.22 was calculated from temporal-intensive soil $CO_2$ flux measurements that were made with automated soil chambers (described below).

Intensive temporal sampling of soil $CO_2$ flux was conducted in a single cornfield within the watershed (field WC15). On day of year (DOY) 170 (5-day prior to the sampling period), six automated chambers were placed in this field at three different landscape elements—two chambers each at a summit, side-slope, and depression location. Soil respiration was measured using automated chambers similar to the design of Parkin and Kaspar (2003). Chambers were 30 cm × 30 cm × 15 cm stainless steel open-ended boxes pressed into the soil approximately 5 cm deep. Chambers were placed in the interrow areas. The top of each steel box was fit with a wooden framework that supported a sliding cover. The covers were supported by casters riding on steel tracks attached to the sides of the chambers. Linear actuators driven by gear motors attached to the frames served to open and close the covers at hourly intervals. Soil respiration was measured every hour by sliding the cover over the chamber top to allow $CO_2$ to accumulate in the chamber headspace. Carbon dioxide was measured during a 6-min period by pumping the chamber gas through an infrared gas analyzer (model LI-800, LI-COR, Inc., Lincoln, Nebraska). After 6 min the chamber lids were withdrawn and the chambers were left open to the atmosphere for the succeeding 54 m. To account for the nonlinear buildup of headspace $CO_2$ concentrations within the chambers, we calculated respiration rates using the algorithm of Hutchinson and Mosier (1981). Each chamber was instrumented with thermocouples to measure air temperature, surface soil temperature, and soil temperature at 5 cm. The average difference between air temperature measured outside the chambers at a height of 1.2 m above the soil surface (in the canopy) and the air temperature within the chambers (0.10 m above the soil surface) during the time they were closed was 1.41°C. We do not know to what extent this difference was a spatial effect (temperatures taken at different heights above the soil surface); however, average air temperature increases within the chamber during the 6 min that they were closed averaged only 0.11°C. The small increases in

[1] Reference to a trade or company name is for specific information only and does not imply approval or recommendation of the company or product by the U.S. Department of Agriculture (USDA) to the exclusion of others that may be suitable.

chamber air temperature were likely results of the fact that the chambers were shaded in the corn canopy. Soil moisture probes, placed in the chambers, were used to measure soil water content (0–6 cm), and a small fan was placed in each chamber to recirculate air during the respiration measurements. Data from the automated chambers were used to determine the diurnal responses of soil $CO_2$ flux in order to account for temperature/time-of-day influences associated with the $CO_2$ fluxes determined with the portable chambers at the remote fields as described above.

### c. *Eddy covariance $CO_2$ flux*

Fifteen eddy covariance towers were spatially distributed across the Walnut Creek watershed, representing multiple soil types and landscape position for both corn- and soybean production fields (Kustas et al. 2005). Two of these towers were in field WC15, where the automated soil $CO_2$ flux chambers were installed. Turbulent fluxes of sensible heat ($H$), latent heat (LE), and $CO_2$ were measured using eddy covariance (Prueger et al. 2004). Instrumentation consisted of a three-dimensional sonic anemometer (CSAT3, Campbell Scientific, Inc., Logan, Utah) and a fast-response water vapor and $CO_2$ density open-path infrared gas analyzer (LI7500, LI-COR, Inc.). The EC instruments were mounted on 10-m towers at 3 m above the ground surface. Ancillary instrumentation on each tower site included a net radiometer [Q*7.1 Radiation Energy Balance Systems (REBS), Seattle, Washington], a high-precision infrared radometric temperature sensor [(IRT), 15° field of view (FOV); Apogee, Logan, Utah] and an air temperature/relative humidity sensor (Vaisala, HMP-35, Campbell Scientific, Inc.). Two soil heat flux plates (REBS HFT-3) were buried 0.06 m below the soil surface—one within the plant row and the second in the interrow space. Soil thermocouples (Cu-Co, type T) were placed 0.02 and 0.04 m below the surface and above each soil heat flux plate.

### d. *Laboratory measurements*

Surface soil (0–6 cm) was sampled at each respiration site. In the laboratory, samples were weighed and sieved (2 mm). Subsamples of the field moist soil were collected for water content and soil microbial biomass, and the remaining soil was air dried. Water content was determined by oven-drying 10 g of field moist soil at 105°C overnight. Soil microbial biomass C was measured by fumigation and direct extraction with 0.5 $M$ $K_2SO_4$ on duplicate 25-g field moist samples (Tate et al. 1988). Organic C in the fumigated and nonfumigated extracts was measured using a Dohrmann DC-180 carbon analyzer (Rosemount Analytical Services, Santa Clara, California). Air-dried samples were ground with a roller mill for organic C and N determination by dry combustion with a Carlo-Erba NA 1500 CHN elemental analyzer (Haakes Buchler Instruments, Paterson, New Jersey) after removal of carbonates (Nelson and Summers 1996). The pH was measured in 1:1 distilled water:soil slurries. Soil texture analyses were performed by Midwest Laboratories, Inc. (Omaha, Nebraska). Physical and chemical properties of the soils are shown in Table 1. Soil respiration potential was performed by placing 5 g of air-dried soil in 120-ml amber tubes equipped with screw tops that were fit with butyl rubber septa. Deionized water was added to each sample to bring the water content to 60% water-filled pore space in order to optimize microbial activity (Linn and Doran 1984). Carbon dioxide concentrations were measured over a 30-day period with an infrared analyzer (Model 2200, Automated Custom Systems, Orange, California). After each $CO_2$ reading, the headspace of each tube was flushed with compressed air. Samples were run in triplicate, and mean respiration rates for each soil sample was calculated from the cumulative amount of $CO_2$ produced over the 30-day incubation period.

### e. *Statistical analyses*

Landscape and cropping effects on soil variables were assessed using two-way analysis of variance (ANOVA) and differences assessed by Tukey's pairwise comparison. Correlations between variables were assessed using the Pearson product moment correlation. All tests were performed with SigmaStat software (SigmaStat, v. 2.03, SPSS, Inc., Chicago, Illinois).

TABLE 1. Site characteristics of soils sampled for SMEX02 study. Presented are average values for all the samples collected within a given landscape element.

| Landscape Position | Sand | Silt | Clay | pH | Total N | Total C |
|---|---|---|---|---|---|---|
| | | (%) | | | (g kg$^{-1}$) | |
| Summit[a] | 52 | 30 | 18 | 5.8 | 1.39 | 16.8 |
| Side slope[b] | 48 | 32 | 20 | 5.8 | 1.85 | 23.3 |
| Depression[c] | 34 | 40 | 26 | 6.3 | 3.14 | 41.4 |

[a] Summit positions were Clarion soils characterized as sandy loams and loams.

[b] Side-slope positions were Nicollet and Clarion soils, characterized as sandy loams and loams.

[c] Depression positions were Okoboji, Canisteo, and Harps soils, characterized as loams and clay loams.

## 3. Results

### *a. Soil respiration and landscape interactions*

Soil respiration rates measured in the field ranged from 10.6 to 93.3 g $CO_2$ $m^{-2}$ $day^{-1}$ across fields and landscape positions within the Walnut Creek watershed (Table 2). The highest rates were observed in field WC15, which was planted with corn, and the lowest fluxes were observed in the soybean fields (WC03, WC14, WC16). Average fluxes for the corn- and soybean fields were 37.5 and 13.1 g $CO_2$ $m^{-2}$ $day^{-1}$, respectively. The analysis of variance showed that there was a crop effect, with the cornfields having significantly higher ($P < 0.014$) fluxes than the soybean fields. While one field showed a significant landscape effect on $CO_2$ flux (field WC16; $P < 0.001$) overall, landscape position was not significant ($P = 0.336$). Also, there was no significant crop × landscape interaction.

While field soil respiration did not show a significant landscape effect, respiration of soil samples that were analyzed in the laboratory exhibited a significant ($P < 0.001$) landscape influence (Table 3). The highest respiration rates were observed in soils collected from depressional areas, while respiration rates of soils collected from summit positions were threefold lower. No significant crop effect was observed.

The microbial biomass content of soil samples followed the same general pattern as the laboratory respirations, with the highest microbial biomass levels present in depressional soils, and lowest levels associated with the summit soils (Table 4). There was a significant landscape effect on microbial biomass levels ($P < 0.047$), but crop had no significant effect.

The landscape and crop interactions with soil organic C are presented in Table 5. Soil organic C results were similar to microbial biomass and laboratory respiration. A significant landscape effect was observed ($P < 0.001$), but the effect of crop was not significant. Also, organic C levels showed the same progression of being lowest in the summit soils, intermediate in the sideslope soils, and highest in the depressional areas.

Soil water content showed significant crop and landscape effects (Table 6). On average, the cornfields had higher soil water contents than the soybean fields, and the depressional areas had higher soil water contents than the summit positions.

Correlation analyses were performed to investigate the interactions between variables (Table 7). For these analyses the corn and soybean data were treated separately. The most striking difference between the corn- and soybean fields was the correlations between field respiration and the other variables. Field respiration in the soybean fields was strongly correlated to microbial biomass and soil water content, and showed weaker, but significant, correlations with texture (sand) and soil organic C. In contrast, soil respiration in the cornfields was not significantly correlated to any of the measured variables. This observation, together with the signifi-

TABLE 2. Soil respiration for individual fields of SMEX02 study. Values have been adjusted for mean daily soil temperature using $Q_{10} = 1.22$. Values for each landscape position within each field are means of three replicate determinations. Values in parentheses are standard deviations. DF: degrees of freedom, SS: sum of squares, MS: mean square; $F$: test statistic from the $F$ Student's $t$ test, $P$: probability (as in $P < 0.05$).

| | Landscape position | | | | |
|---|---|---|---|---|---|
| Crop/field | Summit | Side slope | Depression | Field mean | |
| | (g $CO_2$ $m^{-2}$ $day^{-1}$) | | | | |
| Corn | | | | | |
| WC06 | 18.5 (5.0) | 23.9 (13.1) | 35.6 (5.5) | 26.0 (8.8) | |
| WC13a | 19.2 (2.6) | 22.8 (10.1) | 26.8 (1.8) | 22.9 (3.8) | |
| WC15 | 35.8 (7.8) | 61.4 (26.3) | 93.3 (86.5) | 63.5 (28.9) | |
| Average | 24.5 (9.87) | 42.7 (22.0) | 51.9 (36.1) | 37.5 (22.6) | |
| Soybean | | | | | |
| WC03 | 10.6 (0.04) | 13.7 (3.6) | 11.7 (4.5) | 12.0 (1.5) | |
| WC14 | 12.2 (1.6) | 11.4 (3.5) | 11.6 (3.9) | 11.7 (0.4) | |
| WC16 | 10.6 (0.7) | 12.4 (1.7) | 23.4 (7.1) | 15.5 (6.9) | |
| Average | 11.1 (0.9) | 12.5 (1.1) | 15.6 (6.8) | 13.1 (2.1) | |
| ANOVA | | | | | |
| Source of variation | DF | SS | MS | $F$ | $P$ |
| Crop | 1 | 2681.561 | 2681.561 | 8.329 | 0.014 |
| Landscape | 2 | 769.121 | 384.561 | 1.194 | 0.336 |
| Crop × landscape | 2 | 397.334 | 198.667 | 0.617 | 0.556 |
| Residual | 12 | 3863.660 | 321.972 | | |
| Total | 17 | 7711.676 | 453.628 | | |

TABLE 3. Laboratory respiration of samples from individual fields of SMEX02 study. Values for each landscape position within each field are means of three replicate determinations. Values in parentheses are standard deviations.

| Crop/field | Landscape position: Summit | Side slope | Depression | Field mean | |
|---|---|---|---|---|---|
| | (mg $CO_2$-C g soil$^{-1}$ day$^{-1}$) | | | | |
| Corn | | | | | |
| WC06 | 0.45 (0.051) | 1.02 (0.64) | 1.33 (0.67) | 0.93 (0.35) | |
| WC13a | 0.39 (0.13) | 0.78 (1.03) | 1.34 (0.10) | 0.84 (0.53) | |
| WC15 | 0.28 (0.02) | 0.40 (0.27) | 0.99 (0.28) | 0.56 (0.15) | |
| Average | 0.37 (0.8) | 0.73 (0.32) | 1.22 (0.20) | 0.78 (0.20) | |
| Soybean | | | | | |
| WC03 | 0.38 (0.07) | 0.51 (0.13) | 1.56 (0.76) | 0.81 (0.39) | |
| WC14 | 0.29 (0.02) | 0.41 (0.12) | 0.95 (0.81) | 0.55 (0.43) | |
| WC16 | 0.36 (0.06) | 0.33 (0.04) | 0.95 (0.29) | 0.55 (0.14) | |
| Average | 0.34 (0.05) | 0.42 (0.09) | 1.15 (0.34) | 0.64 (0.15) | |
| ANOVA | | | | | |
| Source of variation | DF | SS | MS | *F* | *P* |
| Crop | 1 | 0.0854 | 0.0854 | 1.835 | 0.200 |
| Landscape | 2 | 2.214 | 1.107 | 23.788 | <0.001 |
| Crop × landscape | 2 | 0.0730 | 0.0365 | 0.784 | 0.478 |
| Residual | 12 | 0.559 | 0.0465 | | |
| Total | | 17 | 2.931 | 0.172 | |

cant crop effect observed in Table 2, indicates that controls on soil $CO_2$ flux may be different in the two cropping systems.

### b. *Relationship of soil respiration to net ecosystem exchange*

Soil temperature, water content, net ecosystem $CO_2$ flux, and soil $CO_2$ flux were monitored continuously from DOY 175 to 185 (Fig. 1). These measurements were made in field WC15 that was cropped to corn. During this period, diurnal 5-cm soil temperature varied from a maximum of 29.2°C to a minimum 21.8°C (Fig. 1a). Daily average daily 5-cm soil temperatures ranged from 26.4° to 28.6°C (an average of 27.6°C over the 11-day time period). Soil water content was highest at the depressional area and lowest at the summit po-

TABLE 4. Microbial biomass levels as a function of landscape position in each field of the SMEX02 study. Values for each landscape position within each field are means of three replicate determinations. Values in parentheses are standard deviations.

| Crop/field | Landscape position: Summit | Side slope | Depression | Field mean | |
|---|---|---|---|---|---|
| | (mg Biomass-C kg soil$^{-1}$) | | | | |
| Corn | | | | | |
| WC06 | 338 (51) | 430 (197) | 914 (414) | 561 (309) | |
| WC13a | 276 (89) | 392 (226) | 407 (62) | 358 (72) | |
| WC15 | 262 (40) | 434 (163) | 387 (84) | 361 (89) | |
| Average | 292 (41) | 419 (23) | 570 (299) | 427 (116) | |
| Soybean | | | | | |
| WC03 | 238 (60) | 314 (66) | 404 (12) | 319 (83) | |
| WC14 | 233 (37) | 283 (16) | 327 (15) | 281 (47) | |
| WC16 | 344 (5) | 335 (55) | 721 (171) | 467 (220) | |
| Average | 271 (63) | 311 (26) | 484 (208) | 355 (98) | |
| ANOVA | | | | | |
| Source of variation | DF | SS | MS | *F* | *P* |
| Crop | 1 | 22 826 | 22 826 | 0.981 | 0.341 |
| Landscape | 2 | 186 097 | 93 048 | 3.999 | <0.047 |
| Crop × landscape | 2 | 6212 | 3106 | 0.134 | 0.0876 |
| Residual | 12 | 279 187 | 23 266 | | |
| Total | 17 | 494 323 | 29 078 | | |

TABLE 5. Soil organic C concentrations as a function of landscape position in each field of the SMEX02 study. Values for each landscape position within each field are means of three replicate determinations. Values in parentheses are standard deviations.

| | Landscape position | | | | |
|---|---|---|---|---|---|
| | Summit | Side slope | Depression | | |
| Crop/field | | (g C kg soil$^{-1}$) | | Field mean | |
| Corn | | | | | |
| WC06 | 21.5 (0.2) | 26.1 (7.7) | 42.0 (9.9) | 29.9 (10.8) | |
| WC13a | 14.8 (3.5) | 22.4 (16.4) | 37.3 (4.6) | 24.9 (11.5) | |
| WC15 | 17.3 (2.9) | 24.5 (1.7) | 40.3 (3.6) | 27.4 (11.8) | |
| Average | 17.9 (3.4) | 24.3 (1.82) | 39.9 (2.4) | 27.4 (2.5) | |
| Soybean | | | | | |
| WC03 | 15.9 (2.5) | 21.0 (6.9) | 42.7 (10.4) | 26.5 (14.2) | |
| WC14 | 15.8 (2.4) | 21.0 (1.5) | 42.0 (3.3) | 26.1 (13.9) | |
| WC16 | 15.6 (1.1) | 18.9 (4.7) | 50.6 (3.6) | 28.2 (19.4) | |
| Average | 15.8 (0.2) | 20.1 (1.3) | 45.1 (4.8) | 27.0 (1.12) | |
| ANOVA | | | | | |
| Variation | DF | SS | MS | $F$ | $P$ |
| Crop | 1 | 0.436 | 0.436 | 0.0580 | 0.814 |
| Landscape | 2 | 2190.468 | 1095.234 | 145.858 | <0.001 |
| Crop × landscape | 2 | 72.068 | 36.034 | 4.799 | 0.029 |
| Residual | 12 | 90.107 | 7.509 | | |
| Total | | 17 | 2353.078 | 138.416 | |

sition. The study area received no precipitation during this time period and soil water content (0–5 cm) declined steadily at all landscape positions. Ecosystem $CO_2$ fluxes measured with eddy covariance exhibited strong diurnal patterns (Fig. 1b). During the daylight hours the canopy was a net sink for $CO_2$, with peak $CO_2$ fluxes approaching $-3$ mg $CO_2$ m$^{-2}$ s$^{-1}$ during the daylight hours. Average nighttime fluxes of $CO_2$ from the canopy to the atmosphere ranged from 0.12 to 0.31 mg $CO_2$ m$^{-2}$ s$^{-1}$. Average daily net ecosystem $CO_2$ flux was $-55.5$ g $CO_2$ m$^{-2}$ day$^{-1}$ (range from $-48.2$ to $-61.6$ g $CO_2$ m$^{-2}$ day$^{-1}$). The trend of decreasing maxi-

TABLE 6. Soil water content as a function of landscape position in each field of the SMEX02 study. Values for each landscape position within each field are means of three replicate determinations. Values in parentheses are standard deviations.

| | Landscape position | | | | |
|---|---|---|---|---|---|
| | Summit | Side slope | Depression | | |
| Crop/field | | (g C kg soil$^{-1}$) | | Field mean | |
| Corn | | | | | |
| WC06 | 0.095 (0.005) | 0.102 (0.034) | 0.190 (0.020) | 0.129 (0.052) | |
| WC13a | 0.084 (0.006) | 0.121 (0.051) | 0.158 (0.039) | 0.121 (0.037) | |
| WC15 | 0.082 (0.003) | 0.124 (0.012) | 0.144 (0.034) | 0.116 (0.032) | |
| Average | 0.087 (0.007) | 0.116 (0.012) | 0.164 (0.023) | 0.122 (0.006) | |
| Soybean | | | | | |
| WC03 | 0.041 (0.011) | 0.050 (0.018) | 0.077 (0.029) | 0.056 (0.019) | |
| WC14 | 0.047 (0.005) | 0.040 (0.004) | 0.086 (0.029) | 0.058 (0.025) | |
| WC16 | 0.097 (0.013) | 0.092 (0.008) | 0.179 (0.021) | 0.123 (0.049) | |
| Average | 0.061 (0.03) | 0.060 (0.028) | 0.114 (0.056) | 0.079 (0.038) | |
| ANOVA | | | | | |
| Source of variation | DF | SS | MS | $F$ | $P$ |
| Crop | 1 | 0.0128 | 0.0128 | 8.769 | 0.012 |
| Landscape | 2 | 0.0126 | 0.00630 | 4.316 | 0.039 |
| Crop × landscape | 2 | 0.00267 | 0.00133 | 0.913 | 0.427 |
| Residual | 12 | 0.0175 | 0.00146 | | |
| Total | 17 | 0.0456 | 0.00268 | | |

TABLE 7. Correlation analyses of soil variables. Shown are Pearson product moment correlation coefficients. Values in bold are significant ($P < 0.05$).

| Soybean | Field respiration | Water content | Laboratory respiration | Sand | pH | % organic C |
|---|---|---|---|---|---|---|
| Field respiration | 1.000 | | | | | |
| Water content | **0.662** | 1.000 | | | | |
| Laboratory respiration | 0.239 | 0.320 | 1.000 | | | |
| Sand | **−0.395** | **−0.592** | **−0.596** | 1.000 | | |
| pH | 0.355 | **0.725** | **0.458** | −0.379 | 1.000 | |
| % organic C | **0.505** | **0.663** | **0.762** | **−0.880** | **0.526** | 1.000 |
| Microbial biomass | **0.713** | **0.879** | **0.448** | **−0.573** | **0.564** | **0.713** |
| **Corn** | **Field respiration** | **Water content** | **Laboratory respiration** | **Sand** | **pH** | **% organic C** |
| Field respiration | 1.000 | | | | | |
| Water content | 0.319 | 1.000 | | | | |
| Laboratory respiration | 0.063 | **0.754** | 1.000 | | | |
| Sand | −0.237 | **−0.700** | **−0.649** | 1.000 | | |
| pH | −0.044 | **0.488** | **0.713** | **−0.471** | 1.000 | |
| % organic C | 0.316 | **0.840** | **0.841** | **−0.785** | **0.454** | 1.000 |
| Microbial biomass | 0.144 | **0.724** | **0.702** | −0.360 | **0.389** | **0.724** |

mum daytime eddy covariance $CO_2$ flux during the study period is likely the result of crop growth. During the time period of DOY 168–183 above-ground corn biomass production increased linearly at a rate of 34.9 grams of biomass per squared meter per day (r2 = 0.9998); and from DOY 183 to 189 the rate of corn biomass production decreased to 28 grams of biomass per squared meter per day. LAI values increased steadily during this time and were 2.66, 3.57, and 4.77 for DOY 179, 183, and 189, respectively.

A diurnal pattern was also noted in the soil $CO_2$ fluxes with the diurnal pattern following that of soil temperature (Fig. 3c). Higher soil $CO_2$ fluxes were observed at the depression position and lower fluxes were observed at the summit position. Also, the amplitudes of the diurnal variations in $CO_2$ fluxes at the summit site appeared dampened compared to the depression site. This may be a result of the lower soil water content at the summit. Over this time period average daily soil $CO_2$ fluxes were 13.4, 10.3, and 7.5 g $CO_2$ $m^{-2}$ $day^{-1}$ at the depression, side-slope, and summit areas, respectively. Averaged over all three landscape positions, daily soil $CO_2$ flux was 10.4 g $CO_2$ $m^{-2}$ $day^{-1}$. From DOY 175 to 181 average daily $CO_2$ flux at the depression position tended to increase, while average daily $CO_2$ flux at the summit position remained relatively constant. Although soil water content was decreasing at all landscape positions, the higher soil water contents at the depression site may have resulted in sustained plant activity (and root respiration) at this landscape position.

Ecosystem respiration was evaluated by assessing nighttime eddy covariance $CO_2$ fluxes and soil $CO_2$

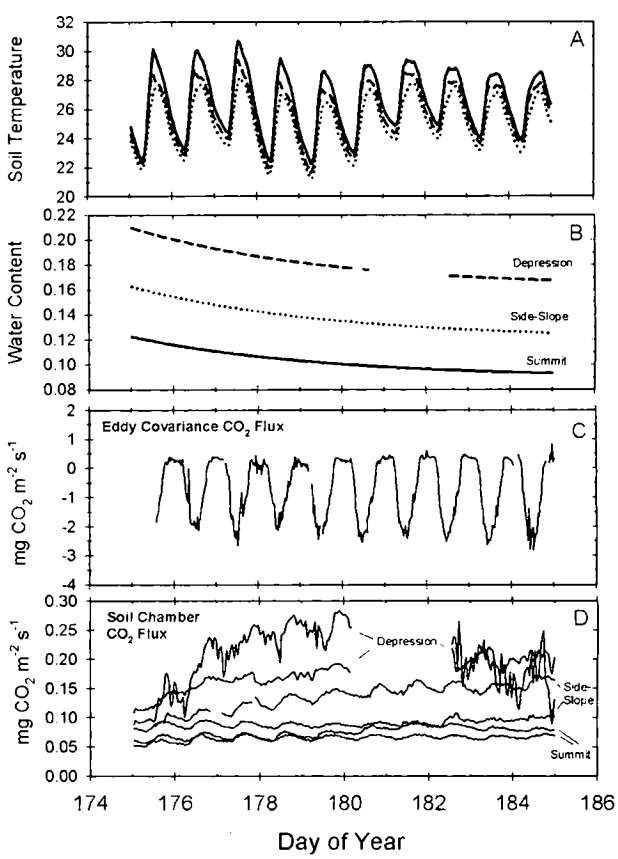


FIG. 1. (a) Soil temperature, (b) soil water content, (c) eddy covariance $CO_2$ flux, and (d) soil chamber $CO_2$ fluxes in Walnut Creek cornfield WC15 from DOY 175 to 185. Note: negative $CO_2$ fluxes indicate consumption of atmospheric $CO_2$ and positive fluxes indicate movement of $CO_2$ from the canopy boundary to the atmosphere. The break in data from DOY 180 to 182.5 at the depression site is the result of equipment failure.

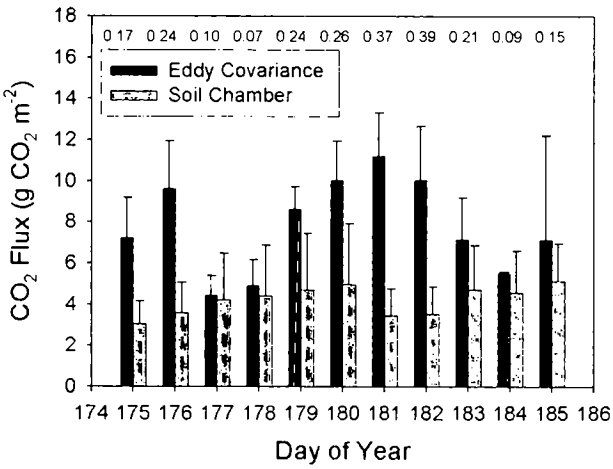


FIG. 2. Comparison of average nighttime $CO_2$ fluxes as measured with eddy covariance and automated soil chambers in field WC15 from DOY 175 to 185. Nighttime fluxes on each day were calculated over the time period of 1900–0500 LST. Means and ranges of two eddy covariance towers, and means and standard deviations of six automated soil chambers are shown. Values across the top of the figure indicate the average nighttime friction velocity (m $s^{-1}$) for each day.

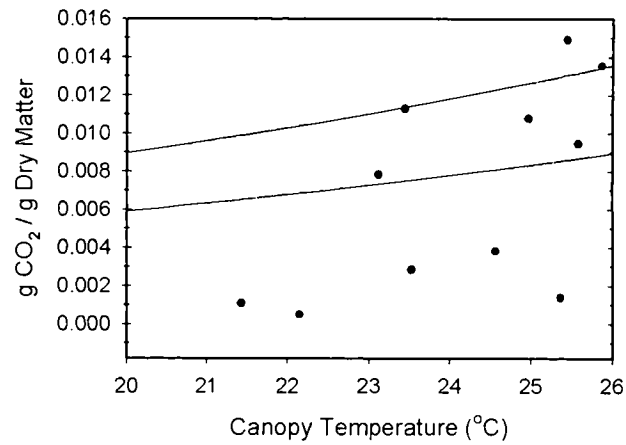


FIG. 3. Average nighttime corn above-ground biomass respiration rates in field WC15 as a function of average nighttime canopy temperature over time period of DOY 176–185. Calculation of above-ground plant biomass respiration was done by subtracting soil respiration from ecosystem respiration at each day (Fig. 2). Values have been divided by above-ground plant biomass to account for crop growth during the sampling period. Also shown are theoretical temperature response curves based on a $Q_{10}$ = 2 relationship calculated using fluxes on days when highest nighttime friction velocities were observed (DOY 181, 182).

fluxes (Fig. 2). Shown are integrated nighttime $CO_2$ fluxes over the time periods of 1900–0500 LST over the study period. Ecosystem respiration is the sum of respiration by above-ground plant material, plant roots, and soil heterotrophic processes. At night, eddy covariance fluxes represent the sum of these components (assuming no substantial buildup of $CO_2$ within the corn canopy), and soil $CO_2$ fluxes represent root and soil heterotrophic respiration. Thus, comparison of these different measurements allows for discrimination between sources of $CO_2$ production. Throughout the measurement period soil chamber nighttime soil $CO_2$ fluxes were relatively constant and ranged from 3.5 to 4.9 g $CO_2$ $m^{-2}$. Eddy covariance fluxes were more variable and ranged from 4.4 to 11.2 g $CO_2$ $m^{-2}$. On half of the nights of the measurement period eddy covariance fluxes exceeded soil $CO_2$ fluxes by a factor of 2 or greater; however, on the other nights (DOY 177, 178, 183, 184, 185), eddy covariance fluxes were lower and only slightly greater than soil $CO_2$ flux. These low-eddy covariance fluxes corresponded to days when turbulence was also low as indicated by the calculated friction velocities.

The observed variations in nighttime eddy covariance $CO_2$ fluxes could be the result of a combination of measurement bias during calm nighttime periods and variations in canopy temperature. Figure 3 shows the relationship between average nighttime canopy air temperature and above-ground plant respiration. Also shown are two curves representing the theoretical $Q_{10}$ response of respiration to temperature calculated using the nighttime fluxes observed on DOY 181 and 182, when friction velocities were highest. The $Q_{10}$ curves can explain the temperature response of six of the observations, however, on the 5 days when friction velocities were low, canopy respiration was lower than would be predicted by canopy temperature differences. This result indicates that eddy covariance fluxes may be underestimates when friction velocity <0.2.

## 4. Discussion

### *a. Landscape effects on soil respiration*

Carbon dioxide flux from soil is largely a biological process, and subject to controls imposed by soil factors such as temperature, water content, aeration status, and organic matter availability. We hypothesized that, because these soil factors vary as a function of landscape position, soil $CO_2$ flux may also be a function of landscape position. However, we observed no significant landscape effect on soil $CO_2$ flux over the time period of our study. This is not to say that landscape position did not have an effect. For example, we did observe significant landscape effects on potential soil respiration measured in the laboratory. Similarly, landscape was a significant factor explaining the variability of soil microbial biomass and soil organic C. There are several important distinctions between field and laboratory res-

piration measurements that may explain the differential effects of landscape on field soil $CO_2$ flux and laboratory soil respiration potential. In the laboratory incubations, the soil had been sieved and mixed; thus, spatial heterogeneity associated with distributions of microorganisms and organic C substrate may have been minimized (Kooistra and van Noordwijk 1995). Also, in the laboratory incubations, soil water content was adjusted to a 60% water-filled pore space—a value that has been found to provide the optimum water availability and aeration for microbial respiration (Linn and Doran 1984). Finally, a critical distinction between field and laboratory respiration is that $CO_2$ production associated with plant roots in the filed was not represented in the laboratory incubations.

Carbon dioxide flux from soil in terrestrial systems is primarily a result of two processes: heterotrophic decomposition of organic material by soil organisms, and root respiration. Root respiration is typically considered to be the result of $CO_2$ produced by the metabolism of plant root cells and, indirectly, from the microbial decomposition of root exudates in the rhizosphere (Wiant 1967). There have been few estimates of the contributions of root activities to soil respiration in corn/soybean production systems. In a recent review of 50 studies, Hanson et al. (2000) identified only 2 in which root and soil respiration were distinguished in a corn production system.

In a study of root and soil respiration in corn plots, Rochette and Flanagan (1997) found that approximately 30 days after planting, root-associated respiration accounted for approximately 10% of the total soil respiration, but 50 days after planting (DOY 195) root activity accounted for approximately 50% of the total soil respiration. These results were confirmed in a later study conducted on a different soil, where Rochette et al. (1999) report that for maize in eastern Canada, root respiration was negligible over the first 30 days from planting, but during the next 30 days of plant growth the contribution of root respiration increased linearly to a maximum of 45% and remained constant until plant senescence. Assessment of the partitioning of soil respiration between corn roots and soil-based processes performed by Prueger et al. (2004) showed similar results, with corn roots accounting for approximately 42% of the total soil respiration. Our study was conducted during the time of active corn and soybean growth (DOY 175–185), approximately 50–60 days after corn planting. Thus, it is likely that root respiration was a significant fraction of the soil respiration values we observed. In a separate study, conducted in 2003, diurnal soil $CO_2$ fluxes were measured in plots with and without living corn roots, and we observed that root respiration accounted for approximately 64% of the total soil respiration (T. B. Parkin unpublished data).

Additional evidence that plant root activity was a major component of our soil $CO_2$ flux measurements is provided by the ANOVA results that indicate a significant crop effect (Table 2). Soil $CO_2$ fluxes in the cornfields were significantly greater than in the soybean fields. The greater crop biomass in the cornfields [average corn above-ground biomass = 466 g $m^{-2}$ on DOY 179 versus average soybean above-ground biomass = 118.9 g $m^{-2}$ on DOY 180 (Anderson et al. 2004)] and, therefore, increased root activity, could be responsible for this difference. Evidence of differential root contributions to soil $CO_2$ flux in the corn- and soybean fields is also provided by correlation analysis (Table 7). In the cornfields, soil respiration was not significantly correlated with any of the parameters considered to be important in controlling microbial activity, such as microbial biomass or organic carbon content. However, in the soybean field we speculate that microbial activity makes a greater contribution to soil respiration, resulting in significant correlations with organic C, water content, soil texture, and microbial biomass.

### *b. Relationship of soil respiration to net ecosystem $CO_2$ exchange*

Net ecosystem $CO_2$ flux is the result of $CO_2$ uptake by plant photosynthesis and $CO_2$ release via plant and soil respiration. In the cornfield of this study (WC15) photosynthesis was the dominant process during the daytime and the field was a net sink of $CO_2$. During the nighttime, plant and soil respiration fluxes were a net source of $CO_2$ to the atmosphere. The balance between day and night fluxes resulted in an overall net ecosystem $CO_2$ flux of $-55.5$ g $CO_2$ $m^{-2}$ $day^{-1}$ (averaged over DOY 175–185). However, net $CO_2$ transfer measured above the canopy does not necessarily reflect the exchange and storage of soil-derived $CO_2$ within the corn canopy. It has been documented that when active corn photosynthesis is occurring, subambient $CO_2$ concentrations (<360 ppm) may exist within a dense canopy. Conversely, at night, canopy $CO_2$ concentrations can increase above ambient levels (Allen 1971; Buchmann and Ehleringer 1998; Lemon 1960; Prueger et al. 2004; Reicosky 1989; Wright and Lemon 1966). Our results showed that nighttime ecosystem respiration averaged 0.22 mg $CO_2$ $m^{-2}$ $s^{-1}$. However, on several of these nights ecosystem $CO_2$ flux may have been underestimated because of low turbulence. In an analysis of errors associated with measurements of net ecosystem

flux, Goulden et al. (1996) report that eddy covariance fluxes underestimate actual fluxes during periods when friction velocity is less than 0.17 m $s^{-1}$. The low nighttime fluxes we observed on DOY 177, 178, 184, and 185 had friction velocities that ranged from 0.07 to 0.15 m $s^{-1}$. The average nighttime $CO_2$ flux during periods when friction velocity was greater than 0.17 m $s^{-1}$ was 0.26 mg $CO_2$ $m^{-2}$ $s^{-1}$. Using this value, we estimate average $CO_2$ flux to the atmosphere to be 9.5 g $CO_2$ $m^{-2}$ $day^{-1}$ during the 10-h dark periods of our study, and, of this amount, 46% (4.35 g $CO_2$ $m^{-2}$) was attributed to soil respiration.

On a 24-h basis, the average production of $CO_2$ by soil respiration was 10.4 g $CO_2$ $m^{-2}$ $day^{-1}$. If canopy interception of this soil-derived $CO_2$ was occurring, the following two questions should be considered: (i) is the $CO_2$ produced from soil-derived respiration processes reflected by above canopy eddy covariance measurements during the daytime, and (ii) is nighttime ecosystem respiration underestimated as a result of storage of $CO_2$ within the canopy? With regard to the first question, it has been suggested by Rochette et al. (1996) that, "Measurements of soil-surface $CO_2$ are needed to complement the above-canopy $CO_2$ flux measured, using micrometeorological methods to calculate $P_n$ (*net photosynthesis*)" (italics added). We agree with this statement and suggest that daytime eddy covariance measurements do not account for soil-derived $CO_2$. This speculation is made based on the fact that during the day a negative $CO_2$ gradient exists (lower $CO_2$ concentrations within the canopy than above the canopy; Prueger et al. 2004). A negative gradient indicates that $CO_2$ produced by the soil (and roots) is not escaping to the atmosphere above the canopy during active corn photosynthesis, but is being consumed within the canopy. The implication of this possibility is that net primary production measured by eddy covariance is underestimated. For the time period reported in this study, the average daily net $CO_2$ flux of −55.5 g $CO_2$ $m^{-2}$ $day^{-1}$ would have to be adjusted by 6.1 g $CO_2$ $m^{-2}$ $day^{-1}$, a factor of 11%.

The underestimate of net primary production described above was based only on consideration of daytime soil $CO_2$ flux. At night, the canopy $CO_2$ gradient is reversed and higher $CO_2$ concentrations have been observed within the canopy than in the overlying atmosphere. However, if significant storage of $CO_2$ occurs during the dark hours, and this $CO_2$ is subsequently taken up by the plant at the onset of photosynthesis the next morning, then this, too, would represent $CO_2$ flux that is not measured by the eddy covariance instrumentation. The consequences of this possibility are evaluated by considering diurnal canopy $CO_2$ concentrations measured in field WC15 (Prueger et al. 2004). These authors report nighttime increases in $CO_2$ within the corn canopy at five different heights (0.15, 0.27, 0.50, 0.90, and 1.65 m), as well as $CO_2$ concentration above the corn canopy (3.0 m). The calculation of canopy storage over the time period of DOY 180–185 was estimated by computing the change in canopy $CO_2$ concentration from its minimum value during the day to its maximum value at night. Over this time period the nighttime enrichment of average canopy $CO_2$ concentrations over ambient levels ranged from 10.7 to 59.7 $\mu$L $CO_2$ $L^{-1}$. Assuming a 2-m-tall canopy, these levels of $CO_2$ enrichment translate to canopy storage of 0.04–0.22 g $CO_2$ $m^{-2}$ during the dark period. These values are small relative to the range of total nighttime respiration over the same sampling period (6.6–12.7 g $CO_2$ $m^{-2}$). From these calculations, we estimate that the nighttime storage of $CO_2$ within the corn canopy accounts for only 0.33%–2.46% of the total dark respiration. Thus, it appears that while failure to account for soil respiration may lead to biased estimates of net primary production, canopy storage of soil-derived $CO_2$ may not be a significant error in measurements of nighttime net ecosystem respiration.

## 5. Conclusions

Results of our work suggest several conclusions. First, while soil respiration potential was significantly correlated to soil properties that were observed to vary as a function of landscape position, soil $CO_2$ flux in the field was not significantly related to landscape position. We conclude that root respiration served to mask any potential landscape effects on soil respiration. Further, it appeared that the contribution of corn roots to soil respiration may have been greater than the soybean root contribution. This may be the underlying reason for the observed significant crop effect on soil $CO_2$ flux. During the study period, approximately 50% of the nighttime ecosystem $CO_2$ exchange was a result of respiration by plant shoots and leaves, and the other 50% was the result of soil respiration (roots and heterotrophic processes). Despite this equal partitioning, the variability in nighttime ecosystem respiration was predominantly associated with canopy temperature effects on plant shoot and leaf respiration. Finally, it is concluded that failure to account for soil respiration may lead to biased estimates of net primary production (underestimated by approximately 11%); however, at night, $CO_2$ accumulation within the corn

canopy is not a significant error in measurement of nighttime net ecosystem respiration.

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