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Nutrient Source and Tillage Effects on Maize: I. Micrometeorological Methods for Measuring Carbon Dioxide Emissions

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Core Ideas

- Aerodynamic methods can be used to gap-fill Bowen ratio energy balance micrometeorological measurements.
- Eddy covariance and Bowen ratio energy balance methods agree during turbulent daytime conditions.
- Measuring nighttime net ecosystem exchange is challenging using turbulence-based micrometeorology.

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ABSTRACT

There is a need to understand the potential benefits of using the biotechnology waste by-product from manufacturing as a fertilizer replacement in agriculture, by quantifying the economic value for the farmer and measuring the environmental impact. Measuring CO_2 emissions can be used to assess environmental impact, including three widely used micrometeorological methodologies: (i) the Bowen Ratio Energy Balance (BREB), (ii) aerodynamic flux-gradient theory, and (iii) eddy covariance (EC). As a first step in quantifying benefits of applying biotechnology waste in agriculture, a detailed examination of these three methods was conducted to understand their effectiveness in quantifying CO_2 emissions for this specific circumstance. The study measured micrometeorological properties over a field planted to maize (*Zea mays* L. var. *indentata*), one plot treated with biotechnology waste applied as a nutrient amendment, and one plot treated with a typical farmer fertilizer practice. Carbon dioxide flux measurements took place over 1 yr, using both BREB and EC systems. The aerodynamic method was used to gap-fill BREB system measurements, and those flux estimates were compared with estimates produced separately by the aerodynamic and EC methods. All methods found greater emissions over the biotechnology waste application. The aerodynamic method CO_2 flux estimates were considerably greater than both the EC and a combined BREB-aerodynamic approach. During the day, the EC and BREB methods agree. At night, the aerodynamic approach detects and accounts for buildup of CO_2 at the surface during stable periods. The BREB systems combined with aerodynamic approaches provide alternate methods to EC in examining micrometeorological properties near the surface.

Abbreviations: BREB, Bowen ratio energy balance; EC, eddy covariance; FP, farmer practice; GHG, greenhouse gas; IRGA, infrared gas analyzer; K, turbulent diffusivity; K_H, turbulent diffusivity for sensible heat; LE, latent energy; MDS, marginal distribution sampling; NEE, net ecosystem exchange; Ri, gradient Richardson number; SMB, spent microbial biomass; $u*$, friction velocity.

Net ecosystem exchange (NEE) of CO_2 is the net vertical CO_2 flux between the soil–plant environment and the atmosphere (Chapin et al., 2006) and is a fundamental measure of C gain and loss from terrestrial systems to the atmosphere. Understanding NEE, and especially how it varies between ecosystems, is critical for understanding climate change on the global scale and how ecosystems emit or sequester C on a regional scale. Micrometeorological (hereafter referred to as "micromet") methods, such as the Bowen ratio energy balance (BREB) and eddy covariance (EC) systems, can be used to measure NEE between the surface (soil and/or plant canopy) and the atmosphere.

Eddy covariance is the most commonly used method for measuring NEE and surface fluxes. Prior to the development of inexpensive three dimensional (3D) sonic anemometers and fast-response open-path infrared gas analyzers (IRGAs), BREB systems were commonly used to estimate NEE, especially for grassland and agricultural ecosystems with short canopies (Angell et al., 2001). Some comparisons between EC and BREB methods yielded similar results (Dugas et al., 2001; Wolf et al., 2008), whereas Alfieri et al. (2009) found considerable differences between the methods for measurement of surface fluxes. Gilmanov et al. (2017) and Skinner and Wagner-Riddle (2012) identified the need for annual studies comparing EC and BREB to evaluate historical BREB data for integration with current EC network data. The BREB systems are commonly used to estimate evapotranspiration (Irmak et al., 2014; Vanomark et al., 2018).

In practice, BREB methods became favored methods within the agricultural community because they could be applied to examine differences among contrasting field treatments involving small plots. On the other hand, EC methods have become the standard for studies of large uniform areas, areas that are usually characterized as "micrometeorologically satisfactory." The confounding issue confronting both communities is the need to ensure that the measurements made at some height above the surface of interest are indeed indicative of the surface itself. To this end, users of BREB methods rely on the assumption that the apportionment of net radiation between ground heat transfer, sensible heat, and latent heat fluxes can be derived using measurements made very close to the surface, whereas EC practitioners require much larger areas to satisfy the standard fetch requirements.

Comparisons between flux measurements made using BREB and EC methods are likely to be difficult due to large fetch requirements of EC. If the EC fetch requirement can be satisfied, then the BREB method loses its special attraction. Comparisons in the past have focused on how to integrate BREB results into an EC flux environment. In the analysis to follow, the intent is largely the opposite, exploring the applicability of micromet flux-gradient methods and EC when the sampled area is a test plot.

Both the BREB and EC methods are based on the turbulent flow of air that transports heat, moisture, and trace gases (e.g., CO_2) between the surface and lower atmosphere. The EC method estimates the vertical fluxes of energy and mass as the covariance of the vertical wind velocity and the energy or mass quantity (i.e., the time average of the product of the mean fluctuation of CO_2 concentration and vertical wind speed) (Scrase, 1930). Aerodynamic flux-gradient methods (referred to subsequently as "aerodynamic methods") rely on measurements of gradients in temperature and wind speed above the surface, and use legacy formulations of the relationships between fluxes and gradients to derive estimates of the relevant fluxes. In essence, the method derives a measure of the appropriate eddy diffusivity, K, which is then used to estimate the fluxes of interest. The BREB method avoids the need to quantify diffusivity from temperature and windspeed measurements by relying on measurements of net radiation as a reference for energy in the system and then apportioning it among the heat fluxes of interest. The EC and aerodynamic methods require large fetch areas to ensure that the results pertain to the surface of interest. The fetch requirement for BREB is comparatively relaxed, because it does not require a direct quantification of the relevant diffusivities, but only to allow for them by assuming that the same diffusivity will apply for water vapor as for sensible heat (Swinbank and Dyer, 1967). In the application considered here, the BREB approach has been used to quantify CO_2 exchange rates, using the diffusivity revealed by the BREB methodology.

During daytime hours, mechanically generated turbulence at the surface (due to the wind and friction with the surface) is augmented by convection resulting from solar heating of the ground and all its components, including soil and vegetation. Over vegetated surfaces, the surface atmosphere is usually unstable during the day (when convection dominates). At night, and in the absence of this radiative heating, the lower atmosphere relaxes and becomes stratified and stable, such that air can decouple into layers within and above the plant canopy. Concentrations of CO_2 from respiration can then build up or pool near the surface. Since EC, BREB, and aerodynamic methods are based on an assumption that the air is well-mixed, strongly stable periods pose challenges for these techniques. The EC systems measure at one fixed height above the canopy and, therefore, may not be able to detect the buildup of CO_2 near the surface but below the fixed measurement height, which could explain why EC tends to underestimate nighttime fluxes during stable conditions (Baldocchi, 2003). Though replacing questionable data can introduce additional uncertainty, a common approach used by the FLUXNET community is to apply a correction factor to adjust nighttime respiration measurements made when friction velocities, u_*, are low (Gu et al., 2005). A global network of more than 900 EC micromet stations measure NEE and other fluxes to understand how CO_2 and other fluxes vary across different types of ecosystems, climate, and land use (Chu et al., 2017).

The BREB calculations are also vulnerable to error in strongly stable conditions (still nights with sporadic turbulence). To make a first-order correction for the errors that may arise, an aerodynamic method, which calculates turbulent diffusivity using canopy height and wind speed, was proposed by Dugas et al. (1999). This aerodynamic method has been used when conditions of strong stability prevail and during other conditions when the BREB method reaches the limits of theory and analytical calculations; these three conditions include: (i) when the difference between the upper and lower temperature and vapor pressure measurements are less than the measurement accuracy of the sensors (Perez et al., 1999); (ii) when the Bowen ratio is near −1 (Ohmura, 1982); and/or (iii) when the moisture or temperature gradient is opposite to the moisture or heat flux direction, respectively (Ohmura, 1982). The BREB method may also experience data losses during mechanical, sensor, or power failures, during which CO_2 flux is linearly interpolated for short periods or omitted from analysis.

Several studies used the aerodynamic method for calculating turbulent diffusivity and CO_2 flux during stable periods and the three conditions mentioned above (Dugas et al., 1999; Frank and Dugas, 2001; Emmerich, 2003; Gilmanov et al., 2003; Mielnick et al., 2005). However, none of these studies compared CO_2 flux calculations with EC systems. A recent study investigated alternative calculations of zero-plane displacement and aerodynamic roughness length, which are inputs used by the aerodynamic method (Graf et al., 2014) and provide an alternate approach to calculate aerodynamic derived turbulent diffusivity.

The specific objectives of this study were to examine the use of the aerodynamic method to fill in gaps of the BREB method by using several approaches for calculating the aerodynamic method and to compare those approaches with NEE calculated by EC systems.

MATERIALS AND METHODS

Site Description

The study site was a 19.1 ha farm in Loudon, TN (35.708° N, −84.373° W, 274 m asl) with a slope of 2 to 12%, as described in Part 2 of this series (O'Dell et al., 2019). The climate is classified as humid subtropical (Cfa) according to Köppen's climate classification with mean annual rainfall of 1245 mm (NOAA, 2019).

Treatment Applications

The field site was split into two areas, both seeded with maize (*Zea mays* L. var. *indentata*), but with one treated with an application of spent microbial biomass (SMB) as explained in Part 2 of this series

(O'Dell et al., 2019). This treatment was applied to the northern 8.4-ha area. The accompanying reference field to the south (10.3 ha) received mineral fertilizer consistent with a typical farmer practice (FP) in place of the SMB. (The reader is referred to O'Dell et al., 2019 for a detailed description of the treatment applications, including application timing and nutrient contents of both SMB and FP applications.)

During the year of flux measurements beginning on 1 Oct. 2016, SMB was applied 12 to 15 June 2017, followed by a surface tillage operation on 16 June 2017. To understand the impacts of tillage on the SMB and FP nutrient effect, the site was subsequently divided into four treatments to allow for incorporation of the SMB, retaining a narrow 30-m no-till strip down the middle of the field for both the FP and SMB. The no-till area was considered to be outside most of the measurement area of the footprint of the micromet instruments.

Carbon Dioxide Flux Measurements

The EC and BREB instruments measured soil and micromet properties from 1 Oct. 2016 to 30 Sept. 2017. A BREB and an EC station were centrally located within each treatment area, with the EC instrument placed 12 m northwest of the BREB instrument. The BREB and EC instruments on the FP plot were placed 155 m north of the field's southern edge and 60 m southwest from the SMB treatment area. The BREB and EC instruments were positioned 68 m north of the SMB plot's southern edge. The EC instruments were oriented 225° southwest in the direction of prevailing winds and maintained at a height 1.75 m above the canopy, adjusted during the growing season. The mean flux source area (footprint) was modeled (Kormann and Meixner, 2001) and showed that more than 80% of EC flux measurements were representative of atmospheric properties within the treatment areas.

The EC fluxes were measured with 3D sonic anemometers integrated with IRGAs (IRGASON, Campbell Scientific, Logan, UT). Coupling the derived vertical velocity signal with temperature data from the same sonic instruments yielded sensible heat fluxes. Similarly, open-path IRGAs measured water vapor and CO_2 concentrations, yielding direct measurement of corresponding eddy fluxes as covariances using the sonic anemometer vertical velocity data. The EC flux data were collected at a 10-Hz sampling frequency.

Despite technological advancements in sensor robustness, EC systems also experience data losses and system failures in addition to the issues associated with nighttime stability. Gaps in data result from equipment or power failures, maintenance, and sensor obstruction, such as from dew, precipitation, or bird droppings. Erroneous CO_2 flux calculations can also result from internal heating of open-path IRGAs during colder temperatures (Bonneville et al., 2008). A survey of EC stations in the global FLUXNET project reported missing or rejected data in a range of 9 to 65%, with a 35% average loss of observations per site (Falge et al., 2001).

Gap-filling strategies have been developed to address data loss and Falge et al. (2001) proposed standardizing methods to improve data comparability. However, Soloway et al. (2017) noted that each gap-filling approach introduces unique biases that should be quantified independently for understanding uncertainties. For this study we used a gap-filling technique commonly used by the FLUXNET community.

This study used REddyProc software (Reichstein et al., 2005; Wutzler et al., 2018) to perform data quality checks and filtering based on the relationship between friction velocity, u_*, and measured flux. REddyProc estimates u_* thresholds and fills gaps in data based on environmental conditions, including recalculation of nighttime fluxes. The first application of REddyProc gap-filling and nocturnal recalculation showed low and negative nighttime fluxes, which were considered to be an effect of the sloping terrain. The planar fit tilt correction (Wilczak et al., 2001) was applied using EddyPro software (LI-COR Biosciences, Lincoln, NE) recalculating most of the raw EC data, followed by the REddyProc marginal distribution sampling (MDS) gap-filling method (Reichstein et al., 2005). The REddyProc MDS method recalculated and/or gap-filled 26% of 30-min EC flux calculations for the FP and 27% for the SMB treatment, consistent with other studies (Falge et al., 2001).

The BREB flux calculations used 5-s average air temperature values, vapor pressure, and CO_2 concentrations measured at two heights above the tops of the vegetation (0.2 and 1.8 m). Measurements were made within aspirated and shielded horizontal air intake tubes facing the direction of prevailing winds (southwest). The BREB systems were built by an in-house team following designs developed elsewhere (Dugas, 1993; Sauer et al., 1998). Vapor pressure and temperature were measured using relative humidity probes coupled with platinum-resistance thermometers (model HC2-S3-L, Rotronic, Switzerland supplied by Campbell Scientific, Logan, UT). Carbon dioxide concentrations were measured with non-dispersive IRGAs (model LI-820, LI-COR, Lincoln, NE). To overcome sensor bias at the two heights, the intake tubes housing the sensors were attached at the end of a rotating arm centrally mounted on a frame that exchanged the sensor position every 5 min. As the crop grew, the rotating arms were elevated so that the lower sensors were always approximately 0.2 m above the crop canopy with the differential between the upper and lower sensors remaining constant. The first 2 min of measurements following each arm rotation were discarded to ensure sample gases were purged from the lines before measuring at the new sample height.

Rainfall was measured with a tipping bucket rain gauge (model TE525, Texas Electronics, Dallas, TX); wind direction and speed were measured with a wind monitor (Model 05305-5, R. M. Young, Traverse City, MI); wind speed was measured with a three-cup anemometer (model 014A, Met One Instruments, Grants Pass, OR); net radiation was measured with a net radiometer (NR Lite2, Kipp & Zonen, Delft, the Netherlands); soil heat flux was measured with soil heat flux plates (model HFT3-L, Radiation Energy Balance System, Seattle, WA); and soil temperatures with Type "T" (copper constantan) thermocouples and buried 0.015 and 0.045 m below the surface.

Five-second measurements were averaged over successive 5-min intervals by the BREB systems and used to calculate 30-min mean CO_2 flux according to BREB system theory (Bowen, 1926; Dugas, 1993; Kanemasu et al., 1979; Tanner, 1960; Webb et al., 1980) using the approach as reported by O'Dell et al. (2018). Five-minute water vapor pressure and temperature differences were averaged over 30-min intervals to calculate the Bowen ratio, which was then used to calculate latent energy and sensible heat fluxes. Sensible heat was used to calculate turbulent diffusivity for sensible heat, K_H, which was assumed to be the same as turbulent diffusivity for CO_2 flux (Monin and Obukhov, 1954). Carbon dioxide flux was then calculated as the product of turbulent diffusivity and the average difference of CO_2 density between the two measurement heights. Thirty-minute CO_2 fluxes were calculated for 365 d between 1 Oct. 2016 and 30 Sept. 2017, after installation and configuration of the BREB and EC stations.

Payero et al. (2003) developed the following inequality relationship to detect the BREB conditions that Ohmura (1982) identified as being inconsistent with the flux-gradient relationship:

$$\lambda(\Delta e+\gamma\Delta T)(R_{\mathrm{n}}-G)>0 \quad [1]$$

where λ is the latent heat of vaporization (J kg^{-1}), Δe is the vapor pressure difference, and ΔT is the difference in air temperature (°C) between the lower and upper position, R_n is the net radiation (W m^{-2}), and G is the soil heat flux (W m^{-2}). The psychrometric constant, $\gamma = (C_pP/\varepsilon\ \lambda)$, where C_p is the specific heat of air (J kg^{-1} $°C^{-1}$), P is atmospheric pressure, and ε is the ratio of the molecular weight of water to that of dry air (0.622).

The following aerodynamic method described by Dugas et al. (1999) was used to calculate turbulent diffusivity when the Payero et al. (2003) test (Eq. [1]) and other tests identified conditions when the BREB method was in question as described above.

The zero plane displacement, d (m), a measure of momentum transfer between surface roughness elements and horizontal flow associated with the flux used in the aerodynamic method was calculated as a function of crop height, h (m) (Stanhill, 1969):

$$\log_{10} d = 0.979\ \log_{10} h - 0.154 \quad [2]$$

Monthly crop height measurements were made throughout the growing season and linearly interpolated. The roughness parameter, z_0 (m), was also calculated as a function of crop height (Tanner and Pelton, 1960):

$$\log_{10} z_0 = 0.997\ \log_{10} h - 0.883 \quad [3]$$

The friction velocity, u_* (m s^{-1}), was calculated from wind speed, u (m s^{-1}) at height z (m), roughness parameter z_0, and zero plane displacement, d, and the von Kármán constant, k, using a value of 0.41 (Dugas et al., 1999) with the following equation (Rosenberg et al., 1983):

$$u_* = \frac{u(z)k}{\ln[(z-d)/z_0]} \quad [4]$$

The change in wind speed to the change in height, $\partial u/\partial z$, was calculated as (Monteith and Unsworth, 2013):

$$\frac{\partial u}{\partial z} = \frac{u_*}{k(z-d)} \quad [5]$$

Equation [4] and [5] are correct only for neutral conditions. In other situations allowance must be made for the role of atmospheric stability. In the present case, measurements were made sufficiently close to the surface that stability effects were generally small. To examine this further, values of the gradient Richardson number, Ri, were computed from gradients of potential temperature, $\partial\theta$ (K) and wind speed ∂u (m s^{-1}) as (Monteith and Unsworth, 2013):

$$Ri = \frac{gT^{-1}\partial\theta/\partial z}{(\partial u/\partial z)^2} \quad [6]$$

where g (m s^{-2}) is the acceleration due to gravity, and T is the absolute temperature (K). Negative Ri numbers correspond to unstable conditions (Dyer and Hicks, 1970) and positive Ri numbers to stable conditions. In stable conditions (mostly at night) the atmosphere stratifies and resists vertical motion (Webb, 1970). As stability increases, turbulence is dampened and the relationships underlying the similarity theory (Monin and Obukhov, 1954) of flux-gradient methods are not valid (Mahrt, 2010). Following Dugas et al. (1999), stability conditions were separated into three categories using the gradient Richardson number: (i) unstable when $Ri < -0.1$; (ii) neutral (aka slightly unstable to stable) when $-0.1 < Ri < 0.2$; and (iii) strongly stable when $Ri > 0.2$. When Ri was greater than 0.2, the turbulent diffusivity coefficient for sensible heat, K_H, was set to 0.005 m^2 s^{-1}.

In unstable conditions when $Ri < -0.1$ when there is a greater upward than horizontal transport of heat, the stability functions for momentum, sensible heat, and water vapor, φ_M, φ_H, φ_W, respectively, were calculated from Ri by the following equation (Dyer and Hicks, 1970) after the conversion of the Monin-Obukhov length L to the Ri number via the relationship $(z-d)/L = (\varphi_M^2/\varphi_H)$ (Monteith and Unsworth, 2013):

$$\varphi_M^2 = \varphi_H = \varphi_W = (1-16Ri)^{-0.5} \quad [7]$$

In conditions when Ri was greater than −0.1 and less than 0.2, the stability functions for momentum, sensible heat, and water vapor were equal and were calculated from results found by Webb, (1970):

$$\varphi_M = \varphi_H = \varphi_W = (1-5Ri)^{-1} \quad [8]$$

Turbulent diffusivity for sensible heat, K_H, was then calculated using the stability function in Eq. [7] and [8] depending on the Ri number with the following equation in an iterative fashion (Campbell, 1985):

$$K_H = ku_*(z-d)\varphi_H^{-1} \quad [9]$$

Carbon dioxide flux was calculated according to methods described in O'Dell et al. (2018) as the product of the turbulent diffusivity for CO_2 flux (assumed to be equal to K_H) and the average difference of CO_2 density between the two measurement heights. The flux was corrected for vapor pressure and temperature differences at the two measurement heights according to Webb et al. (1980).

To evaluate the use of this aerodynamic method, we applied a recent method for calculating the zero plane displacement and the roughness parameter by Graf et al. (2014). Because the EC systems provided direct measurements of friction velocity, one aerodynamic method was developed using the EC u_* measurements for comparison with calculations of u_* and CO_2 flux from BREB station wind speed measurements.

In recognition of the distinctions among the alternative methodologies described above, and of the differences of their results in (primarily) nighttime conditions, several comparisons were conducted. The results of these tests are presented below.

Data Analysis

Missing data resulting from power loss, or the failure of one or more critical sensors for periods greater than 8 h, resulted in approximately 6% data loss for the BREB and aerodynamic methods. During data loss periods of less than 8 h, fluxes were linearly interpolated; this occurred for less than 1% of observations. Although no power losses or sensor issues occurred for the EC stations, approximately 3% data loss occurred due to rain events and were gap-filled using REddyProc.

We created five analytical methods to compare 30-min fluxes and to evaluate the effect of different aerodynamic inputs such as canopy height estimation and wind speed on the calculated flux. A description of each follows:

1. "BREB-Aero" is a combined method using BREB when it satisfied the conditions as described above and using the aerodynamic method when it did not. The aerodynamic method included the zero plane displacement (d) as a function of crop height as described by Dugas et al. (1999) and in lieu of wind measurements at the BREB stations, friction velocity, u_*, from the EC stations was used in the aerodynamic calculations.
2. "Aero-Stanhill" is an aerodynamic-only method using the results of Stanhill (1969) to calculate d, the zero plane displacement (Eq. [2]). Tanner and Pelton's (1960) method was used to calculate z_0 (Eq. [3]). This method used the wind speed measured at each BREB station.
3. "Aero-Graf" refers to an aerodynamic-only method, which uses the method described by Graf et al. (2014) to calculate d and z_0. This method used the wind measured at each BREB station.
4. "Aero-EC u_*" is an aerodynamic-only method that uses the u_* derived from EC measurements to calculate the change in wind speed to the change in height in Eq. [5] and d is calculated according to Eq. [2] as described above.
5. "EC" are the flux calculations produced by the EC instruments after planar fit tilt correction, gap filling, and flux recalculation.

RESULTS AND DISCUSSION

Table 1 provides a summary of annual totals of NEE in g CO_2 m^{-2} yr^{-1} for both FP and SMB treatments for each of the five methods evaluated. The aerodynamic-only methods (Methods 2, 3, and 4) show considerably greater NEE for both treatments. From an initial assessment of the five flux calculation methods, it was found that the aerodynamic-only methods (Methods 2, 3, and 4) underestimated daytime fluxes during the growing season compared with EC (Method 5). However, the combined BREB-aerodynamic method (Method 1) more closely resembled the EC method daytime fluxes, which is consistent with other studies (Dugas, 1993; Angell et al., 2001).

The NEE evaluations calculated by the three aerodynamic-only methods (Methods 2, 3, and 4) were similar during the daytime when averaged over 2-wk periods sorted by time of day and atmospheric stability (data not shown). Although these methods could be used when the BREB method does not effectively calculate flux during stable periods at night or when the differences in the temperature or vapor pressure gradient is close to zero, the aerodynamic-only methods produced total accumulated NEE that exceeded both the EC method and the combined BREB-aerodynamic method (Table 1). The aerodynamic method that used the EC u_* (Method 4) produced the lowest flux of the three aerodynamic-only methods (Table 1). This may be due, in part, to greater accuracy of wind speed measurements at lower wind speeds by the EC system sonic anemometers compared with the BREB systems' mechanical anemometers that had higher starting thresholds for wind speed detection (minimum detection > 0.4 m s^{-1}) (Monteith and Unsworth, 2013).

The combined BREB-Aero method calculated 34% of the CO_2 flux using the BREB method for the FP treatment and 36% of CO_2 flux was calculated using the BREB method for the SMB treatment, with the remaining periods gap-filled with CO_2 flux calculated using the aerodynamic method. Much of the excluded BREB flux was due to atmospheric stability because 41% of atmospheric conditions over the FP and 38% over the SMB field were identified as stable conditions. These numbers are higher than other studies that substituted the aerodynamic method for the BREB method. Dugas et al. (1999) estimated its use at 10%, Frank and Dugas (2001) about 10%, Emmerich (2003) about 12%, Gilmanov et al. (2003) about 14%, and during a 6-yr study Mielnick et al. (2005) estimated that 23% of their flux data was gap filled due to BREB issues.

The aerodynamic-only methods (Methods 2, 3, and 4) showed less negative daytime flux during the growing season than both the combined BREB-Aero (Method 1) and EC (Method 5), and greater negative flux during the non-growing season (data not shown). Subsequent analysis to understand the differences between the methods used one aerodynamic-only method (Method 4) that used the EC u_* and produced fluxes more consistent with EC than the other two aerodynamic only methods.

The accumulated annual CO_2 flux for the SMB and FP treatments were compared and plotted for three methods in Fig. 1—the combined BREB-Aero Method 1, the aerodynamic-only Method 4 that uses the EC u_*, and the EC Method 5. Flux measurements began during the non-growing season, which shows a small buildup of CO_2 from October 2016 through February 2017, where respiration exceeded photosynthesis with positive fluxes indicating a net transfer of CO_2 from the soil to the atmosphere. Figure 1 shows that emissions appear to level off and even decrease (negative slope) in April and May 2017, corresponding to spring weed growth. Emissions resumed following herbicide application on 31 May 2017 and biomass application and tillage on 16 June 2017. The rate of positive fluxes (steeper slope) increased mid-June until the maize canopy reached the V5 vegetative state around 10 July 2017, when photosynthesis from the growing canopy exceeded day and night respiration, at which time the slope becomes negative, indicating net C sequestration. Maize senescence occurs at the end of August 2017, showing the end of sequestration (Fig. 1).

A comparison of CO_2 flux (g m^{-2} h^{-1}) by time of day for the beginning of the non-growing season from 1 Oct. 2016 through 31 Jan. 2017 combined is shown in Fig. 2 for the BREB-Aero Method 1,

Table 1. Total NEE (g CO_2 m^{-2} yr^{-1}) for each method from 1 Oct. 2016 to 30 Sept. 2017.†

Treatment	Method 1 BREB-Aero	Method 2 Aero-Stanhill	Method 3 Aero-Graf	Method 4 Aero-EC u_*	Method 5 EC
			g CO_2 m^{-2} yr^{-1}		
SMB	1699	3498	3789	2460	794
FP	232	1016	1174	685	274

† FP, farmer practice; NEE, net ecosystem exchange; SMB, spent microbial biomass.

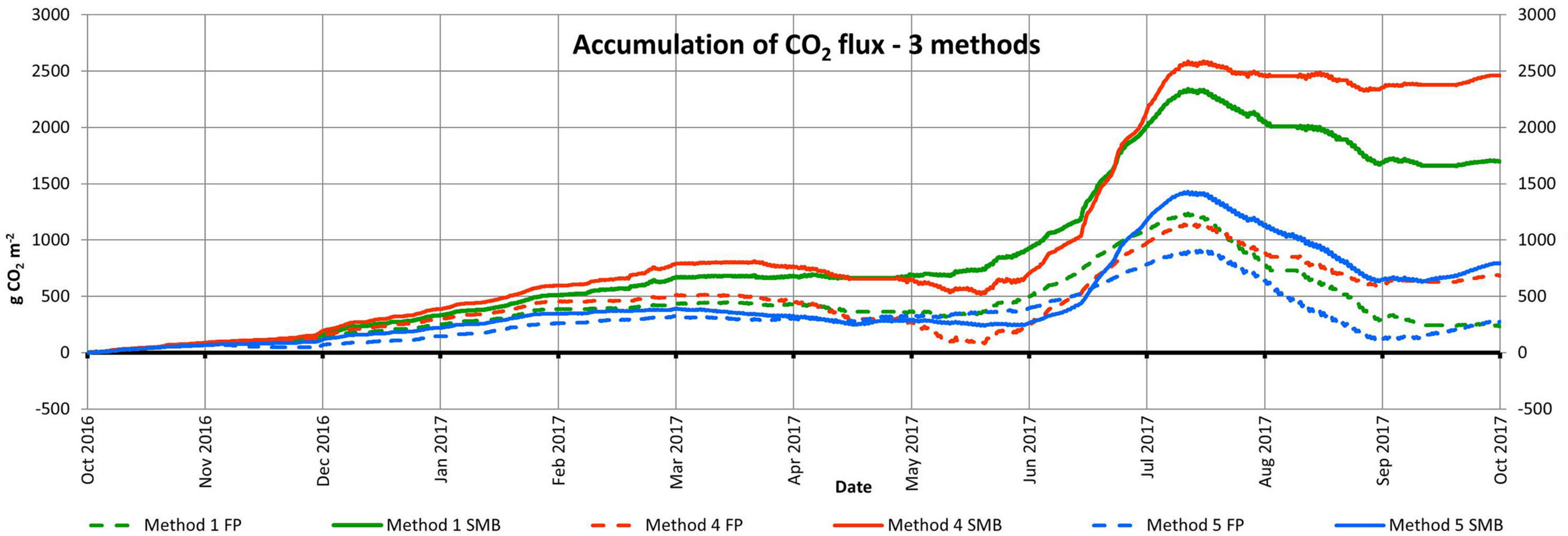

Fig. 1. Carbon dioxide flux accumulation shown for the BREB-Aero (Method 1), Aero-EC u_* (Method 4), and EC (Method 5) for both treatments with the FP treatment shown with dashed lines and the SMB treatment solid lines.

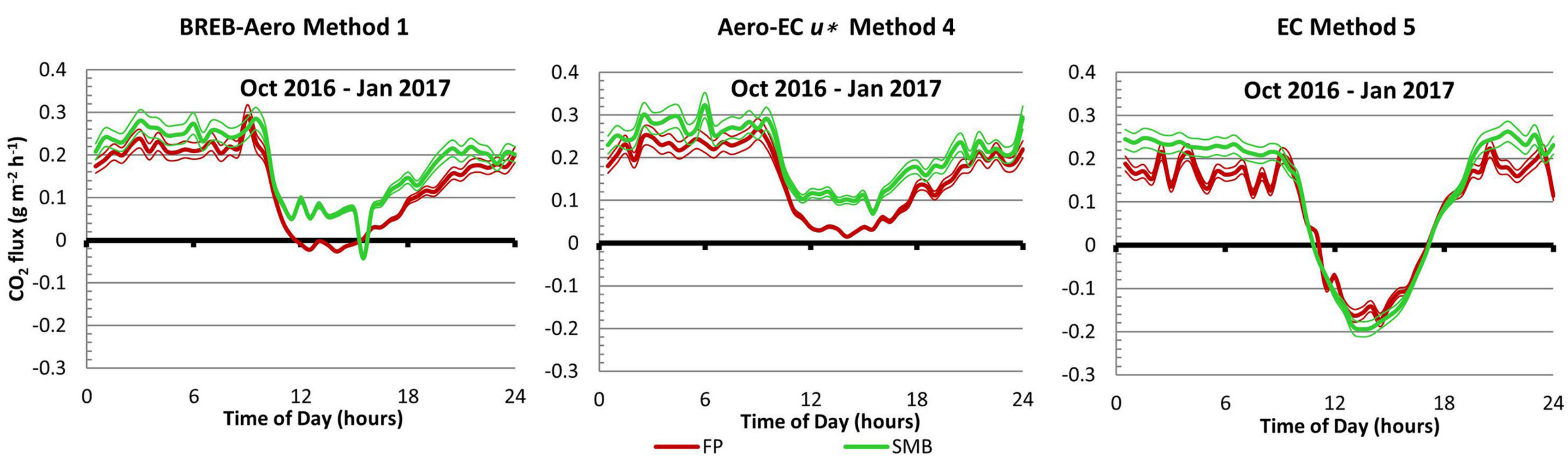

Fig. 2. Carbon dioxide flux by time of day for the first 4 mo for BREB-Aero (Method 1), Aero-EC u_* (Method 4), and EC (Method 5) for FP (red) and SMB (green) treatments ±1 SE.

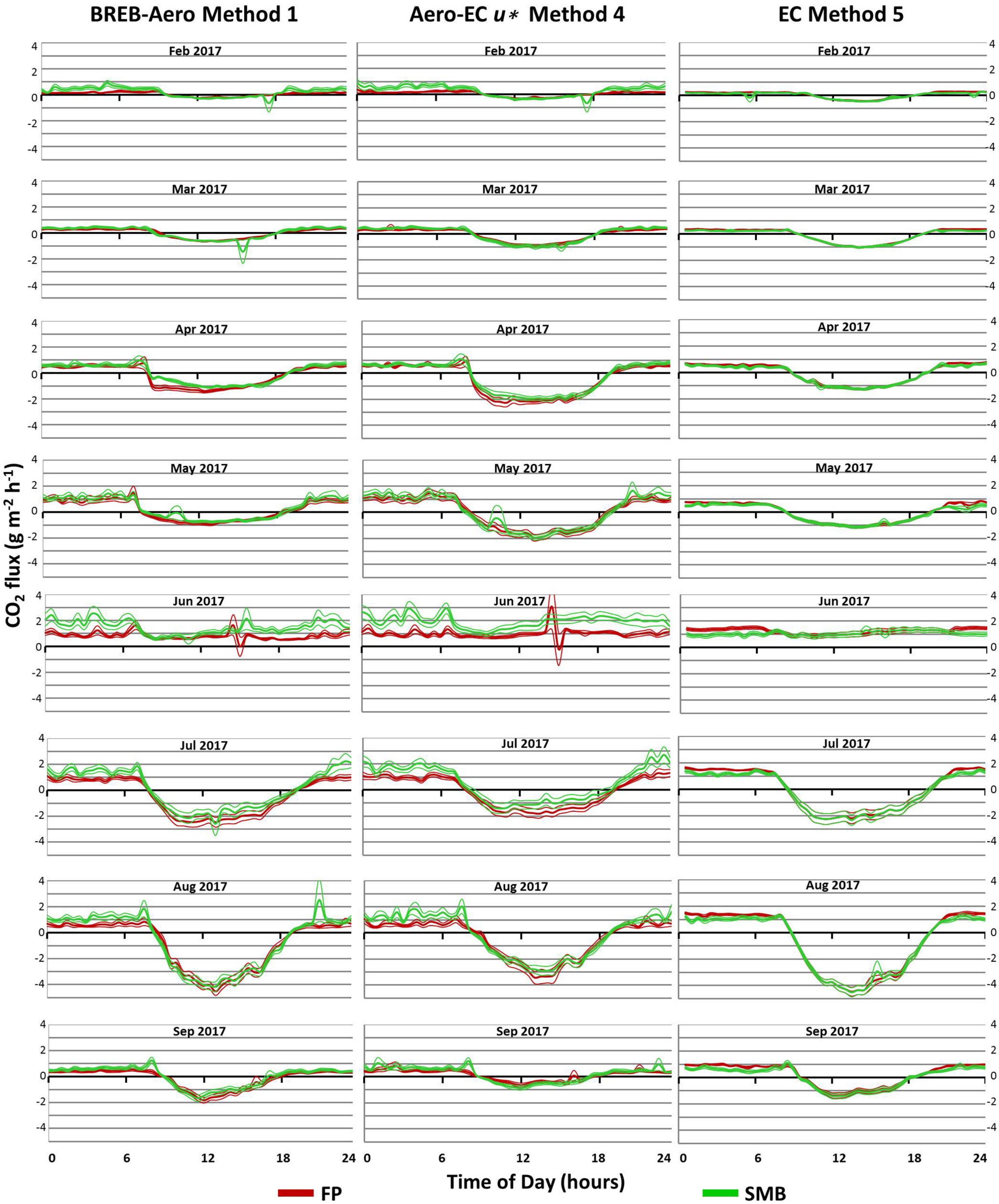

Fig. 3. Carbon dioxide flux by time of day and month for BREB-Aero (Method 1), Aero-EC u_* (Method 4), and the EC (Method 5) for FP (red) and SMB (green) treatments ±1 SE.

the Aero-EC u_* Method 4, and the EC Method 5 when fluxes were small and similar by time of day. The EC method generally showed greater daytime sequestration from weed growth during this period, whereas the combined BREB-Aero and Aero-only methods generally showed net positive CO_2 emissions during the day. The SMB treatment showed greater night emissions than the FP for all three methods.

Figure 3 shows a comparison of flux by time of day and month from February to October 2017 for Methods 1, 4, and 5 at a scale more than 10 times greater than Fig. 2 to account for greater fluxes during the growing season. Generally, the combined BREB-Aero method (Method 1) is more similar to the EC method (Method 5) during the daytime hours during the growing season (July–September 2017), when the greatest photosynthesis is taking place. The Aero-EC u_* method shows greater negative daytime CO_2 fluxes than the EC and combined BREB-Aero methods in the spring during April and May 2017. Further, the Aero-EC u_* method shows less negative daytime flux than both the combined BREB-Aero and EC methods during the growing season from July through September, raising questions about the aerodynamic method's (Method 4) ability to estimate daytime CO_2 flux. Figure 3 also shows that the EC method (Method 5) indicates greater emissions for FP treatment than the SMB treatment at night during the growing season (June–September) than the BREB-Aero and Aero-EC u_* methods. This phenomenon is unexpected and could be an artifact of the planar fit tilt correction and/or the REddyProc nocturnal recalculation.

There is considerable agreement between BREB and EC during the day (Fig. 3), providing evidence that these two methods accurately estimate CO_2 flux. The EC method is widely used and is considered accurate during the daytime. The daytime aerodynamic estimates raise questions about using the aerodynamic method during daytime conditions. The aerodynamic method (Method 4) often overestimated daytime flux during cool temperatures and underestimated daytime flux during the growing season with respect to EC and BREB. The biggest question for EC flux measurements and all of these methods concern nighttime conditions, when the EC method has been known to underestimate flux (Aubinet, 2008). Nighttime BREB fluxes are most often replaced with the aerodynamic method, and this approach generally disagrees with the EC method. It is not clear whether the EC or the Aerodynamic method is a better estimate of CO_2 flux at night. The following example explores some of the nighttime variable interactions.

Because of frequent stable conditions at night with low wind speed and thermal stratification of the lower atmosphere, CO_2 concentrations can build up at the surface and are not detected by the EC system. During these periods the BREB-Aero method detects differences in CO_2 concentrations where the lower sensor reads as much as 117 μmol CO_2 mol^{-1} air higher than the upper sensor as demonstrated in Fig. 4 (the purple circle) during a 5-h period on 17 June 2017 at 0200 h following biomass application and surface tillage completed on 16 June. This example shows the difference in CO_2 concentrations between the lower and upper sensors measured by the SMB BREB station, along with the calculation of CO_2 flux for the combined BREB-Aero and Aero-EC u_* (Methods 1 and 4). All fluxes are the same for these two methods (Method 4 in red directly tracks and overwrites Method 1 in green), signifying that during this stable period, the aerodynamic method was used to calculate CO_2 flux in place of the BREB method because conditions were consistent with Ohmura's criteria for rejecting Bowen ratio flux calculations (Ohmura, 1982). This one 5-h example period demonstrates how the CO_2 flux calculated by the aerodynamic method follows the increases and decreases of the CO_2 concentration difference between the two heights (Fig. 4).

This buildup of CO_2 near the surface is identified as a storage term in the quantification of CO_2 flux (Finnigan, 2006; McHugh et al., 2017; Yang et al., 2007). During stable periods at night (1–3 h length), CO_2 concentrations will increase at the soil or canopy surface until disbursed by bursts of turbulence described as nocturnal intermittency (Hicks et al., 2015). Although both EC and BREB systems detect the turbulent dispersion of CO_2 often with a spike in flux, only the concentration profile provided by the BREB station can detect the surface buildup of CO_2 before the intermittent turbulence. Using the aerodynamic method, this concentration difference can be accounted for in the NEE using a very conservative constant for the turbulent diffusivity coefficient (0.005 m^2 s^{-1}), which is proscribed by

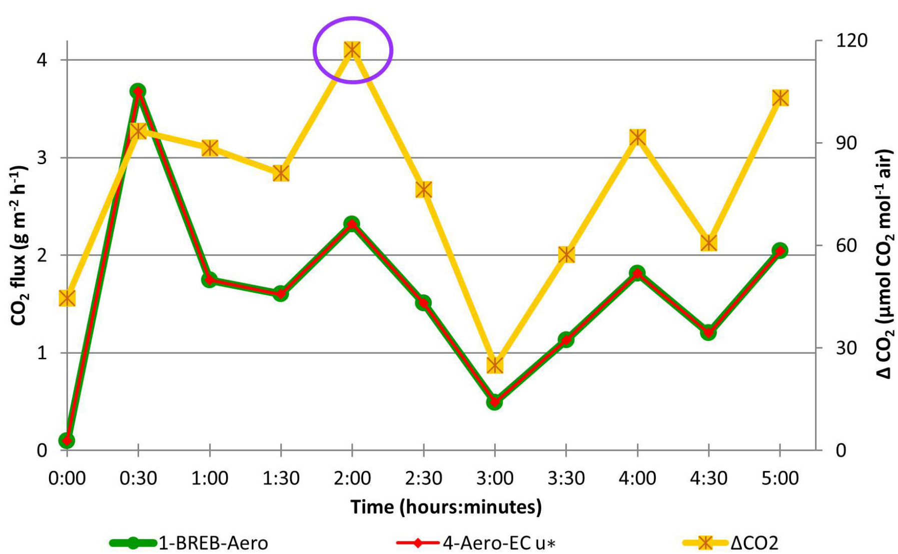

Fig. 4. Half-hour CO_2 flux for the BREB-Aero (Method 1) and Aero-EC u_* (Method 4) from 0000 to 0500 h on 17 June 2017 with 30-min average CO_2 concentration differences between lower and upper sensor at the SMB BREB station. The purple circle indicates the maximum CO_2 concentration difference of 117 μmol CO_2 mol^{-1} air during this period.

the aerodynamic method during stable periods (Dugas et al., 1999). By using this constant the combined BREB-aerodynamic method system can more effectively estimate nighttime respiration that may be underestimated by EC. Given concerns about underestimating nighttime EC flux, the combined BREB-aerodynamic method may provide a more conservative estimate of the total emissions for use in quantifying environmental impact and the potential to sequester C.

When conditions are "favorable" (i.e., "turbulent") during the day, the EC and BREB methods agree. In comparison, the lack of nighttime turbulence poses challenges for measuring NEE using turbulence-based methods such as EC, BREB, and aerodynamic methods. The data presented in this study showed that during the night, the EC and aerodynamic method generally did not agree. Additional work is needed that focuses on the pooling and drainage of CO_2 at the surface during stable conditions at night. Although the network of EC stations seeks to increase understanding of the carbon cycle in agriculture and other ecosystems, profiles of meteorological measurements as provided by BREB and other approaches can be used to understand the nighttime buildup of CO_2 and other atmospheric characteristics near the surface. This complexity needs to be addressed using both spatial differences and turbulent exchanges.

CONCLUSIONS

Multiple instruments and five methods were used to calculate CO_2 flux over two contrasting treatments and all methods showed greater CO_2 emissions over the spent microbial biomass treatment compared with the farmer practice. Total NEE estimates produced by the aerodynamic methods were considerably greater than both the EC and a combined BREB-aerodynamic approach. During daytime turbulent conditions, the EC and BREB methods agree. Of particular interest was investigating the nighttime flux which can be underestimated by the EC method. BREB fluxes are most often replaced by the aerodynamic method at night when the BREB method approaches the limits of flux-gradient theory. The combined BREB-aerodynamic method was able to detect and account for the pooling of CO_2 near the surface during stable periods at night. Alternate flux-gradient micromet approaches, including BREB and aerodynamic methods, generally showed greater total NEE estimates for both treatments and can be used to estimate nighttime flux, especially during periods of low turbulence when micromet techniques are challenged.

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