Attribution of Carbon Dioxide Fluxes to Crop Types in a Heterogeneous Agricultural Landscape of Argentina

Gabriela Posse · Klaus Richter · Nuria Lewczuk · Piedad Cristiano · Natalia Gattinoni · César Rebella · Antonio Achkar

Abstract The increasing proportion of agricultural lands worldwide makes it necessary to intensify the research concerning the carbon exchange at agricultural sites. In order to determine the Net Ecosystem Exchange (NEE) in an agricultural landscape in the province of Buenos Aires, Argentina, we carried out eddy covariance measurements with a flux tower, which was placed between two agricultural fields. Therefore, the measured CO_2 flux represents the accumulated flux from both areas, i.e., from different crop types. We here present an analysis method which attributes the flux to the two crop types. For this analysis, we applied the Hsieh footprint model to identify the contributing source area to the flux measurement. We then applied a multiple regression analysis to calculate the NEE in the growing season 2011/2012 for each field separately. The pronounced differences in the time courses of the CO_2 fluxes in the two fields can be explained by the different sowing times and different growth stages of both cultivations. The time courses furthermore show that the CO_2 uptake of the plants was strongly affected by the drought which lasted from December 2011 to January 2012. For the growth cycle of maize (216 days), the NEE was -240 g C m^{-2} and for the growth cycle of soybean (154 days) -231 g C m^{-2}. In order to obtain the NEE of a complete agricultural cycle (from harvest to harvest), we also considered the NEE of autumn and winter 2011. Uncertainties of the spatially partitioned NEE are quantified and discussed.

1 Introduction

The increase of CO_2 and other greenhouse gas (GHG) concentrations in the atmosphere led to many activities with the aim to quantify and to mitigate the increase of GHG emissions, e.g., establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988 and implementation of the Kyoto Protocol in 1997. The measurement of GHG fluxes in ecosystems and the identification of the environmental variables, which determine the interaction between biosphere and atmosphere, are one of the activities which contribute to an understanding of the interaction between GHG and climate. Nowadays, the carbon balance between atmosphere and biosphere is studied worldwide with around 500 flux towers (http://www.fluxnet.ornl.gov), which use the eddy covariance technique [e.g., 1–3] to measure CO_2 fluxes [4–6]. The advantage of the technique is that it measures the carbon flux of an ecosystem as a whole and that it, due to its high temporal resolution, allows the integration of fluxes over timescales of hours to an entire growing season. Most of the towers are installed in North America and Europe in ecosystems with different vegetation types, such as forests, croplands, grasslands, shrublands and permanent wetlands. In South America, most of the towers are in the Amazonian rain forest and the tropical climate region.

The interest in managed ecosystems has increased in the last years [7–10]. Although fossil fuel combustion has been

G. Posse · K. Richter (✉) · N. Lewczuk · P. Cristiano · N. Gattinoni · C. Rebella
Instituto de Clima y Agua—Instituto Nacional de Tecnología Agropecuaria (INTA), N. Repetto y De Los Reseros s/n, 1686, Hurlingham, Provincia de Buenos Aires, Argentina
e-mail: krichter@cnia.inta.gov.ar

A. Achkar
Universidad Católica de Santa Fe, Área Informática, Echagüe 7151, Santa Fe, Provincia de Santa Fe, Argentina

N. Lewczuk · P. Cristiano
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Buenos Aires, Argentina

the major cause of increasing CO_2 in the atmosphere, land use modifications are also a significant CO_2 source. The expansion of annual cropping systems into forest and grasslands are suspected to be responsible for 20–25 % of the increase in atmospheric CO_2 that occurred over the last 150 years [11]. It has been recognized that farm management (cultivated crop types, crop sequences, application of fertilizers) is a principal factor that may explain the controls of source/sink of carbon [12]. For example, no-tillage practice is more carbon conservative than traditional management, and maintaining a year-round green cover is more beneficial [13]. Agricultural ecosystems deserve special attention because agricultural lands occupy about 37 % of the earth's land surface [14] and the area is expected to increase to meet rising food demand [15]. In Argentina, more than 30 million hectares are dedicated to agricultural cultivations of soybean, wheat, maize and other cereals and oil plants. A broad spectrum of crop types is in particular found in areas with very fertile soils, as in the Pampas region, with the consequence that there agricultural fields with different crops often lie close together.

The eddy covariance technique integrates CO_2 fluxes from a source area which are upwind of the flux tower. Agricultural fields which are smaller than the footprint may pose a problem for the evaluation of the eddy covariance fluxes [16]. The issue of CO_2 fluxes measured with flux towers in areas with mixed vegetation, covered by different crop types or by forests, agriculture and pasture, has been addressed by some authors [17–20] and different methods to spatially attribute fluxes measured with flux towers or aircrafts have been proposed [e.g., 21–24]. The principal objective of our work is to present a methodology that allows the determination of individual fluxes of a specific land cover in a heterogeneous area from a continuous single point measurement. First, we tested the reliability of the methodology by using two synthesized CO_2 flux time series, which were superposed according to the footprint source area. We then applied the methodology by using our eddy covariance measurements in an agricultural area where two different crops were cultivated on adjacent fields, namely maize (*Zea mays* L.) and soybean (*Glycine max* (L.) in order to obtain the spatially partitioned fluxes and the net ecosystem exchange (NEE) of each field for the considered period (from September 2011 to April 2012). The study was completed with an error consideration of the NEE values.

2 Material and Methods

2.1 Study Site

The fields where this research was conducted are at a private property located 2 km from Mercedes city (Buenos Aires province, Argentina), 59° 28′ 31.7″ W; 34° 38′ 29.7″ S, and 110 km West of the city of Buenos Aires. The terrain of the area is nearly flat, at 35 m asl, and the soil group is phaeozem (FAO soil classification). The two fields are directly adjacent, separated only by a wire fence (Fig. 1). The metallic tower with the eddy covariance instruments was located on the borderline of the two fields. Both fields have not been tilled for at least 15 years, with a region-typical 4-year crop rotation of soybean, maize, wheat and oat. In the season 2010/2011 soybean was cultivated on both fields and harvested on April 15, 2011. In the following wintertime the fields were not managed and weeds appeared. The weeds were removed with an herbicide (glyphosate), which was applied on August 15, 2011. Maize and soybeans were sown on September 19, 2011 and November 12, 2011 on the northwestern and southeastern field, respectively. A severe drought affected both cultivations and the maize plants withered. Soybeans were harvested on April 14, 2012, while the maize was not harvested due to poor plant development.

For the period between September 1 and April 30 the historical mean temperature is 19.8 °C and the total precipitation is 786 mm (climatic statistics 1971–2000, INTA). The precipitation in this period for 2011/2012 was 532 mm, 254 mm lower than the mean of the historical record. Mean temperature was 19.9 °C, almost the same as the historical record. The daily maximum of the air temperatures in the measurement period was between 15 °C and 34 °C. There were only 11 days with precipitation. Measurements of PAR (photosynthetically active radiation) were carried out with a GaAsP photodiode (Cavadevices.com, Buenos Aires, Argentina) installed at 1.5 m height and 4 m from the tower. Global radiation has been estimated by multiplying the photosynthetic photon flux density with 0.5 J μmol^{-1} [25, 26].
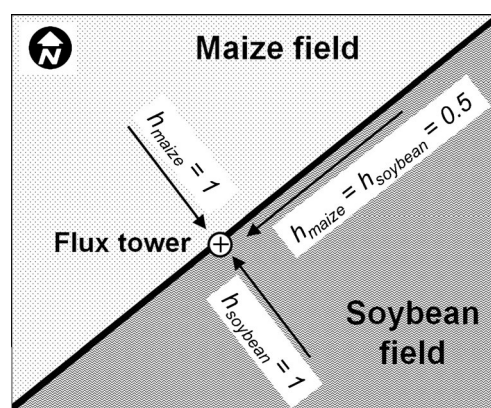

Fig. 1 Scheme of the measurement arrangement. The flux tower is placed between a maize field and a soybean field. The footprint portions h_{maize} and $h_{soybean}$ of the two cultivations can adopt values between 0 and 1. The values depend on the wind direction (indicated by the exemplary *arrows*) and are calculated with a footprint model. If $h_{maize}=1$, then $h_{soybean}=0$ and vice versa. If $h_{maize}=h_{soybean}=0.5$, then the wind comes along the borderline

2.2 Eddy Covariance Instruments and Data Processing

The eddy covariance instruments used were a 3D sonic anemometer (USA-1, Metek, Elmshorn, Germany) and a LI-7500 Open Path CO_2/H_2O Infrared Gas Analyzer (Li-Cor Inc., Lincoln, Nebraska, USA). The instruments were mounted on a 6-m-high scaffold tower at a height of 3.5 m. Due to the filigree structure of the tower, it is assumed that flow distortion is negligible. The raw data from the anemometer and the analyzer were stored with a Panel PC (Sysmedia S.r.l., Italy) at a frequency of 20 Hz. The data were processed using an in-house software, which successfully passed an intercomparison test with golden files (carried out by the Oak Ridge National Laboratory, Tennessee, USA, http://public.ornl.gov/ameriflux/gold-open_path.shtml). The data processing included standard procedures such as de-spiking [27], block averaging for the covariance calculations, maximizing of the covariance magnitude to correct for the time-lag between anemometer and analyzer and two-dimensional rotation [28] of the anemometer coordinate system. The data of the anemometer type (Metek USA-1) require a further correction due to lateral wind [29]; the sonic temperature was converted to air temperature [30]. A frequency response correction was applied [31, 32] and the fluxes were calculated by taking into account the fluctuation of air densities due to water vapor and temperature [33, 34]. The flux values were flagged to assess the condition of steady state within a half-hour measurement period [35]. The random error of CO_2 flux measurement was calculated with the method described by Hollinger and Richardson [36].

For the present study we used a measurement period that comprises the whole growing season of maize and soybean and is therefore appropriate for the application of a methodology that attributes measured fluxes to different crop types. The data included in the present study corresponded to 60 % of the analysis period. The missing data were caused by sensor failures and by elimination of data: data that did not pass the steady state test were eliminated, as well as nighttime fluxes at non-turbulent conditions based on a u*-criterion [1, 37] with a u*-threshold of 0.1 m s^{-1}.

2.3 Footprint in the Maize and Soybean Field

Since the sensors were at the borderline of two fields cultivates with different crop species, the CO_2 flux measured represents the accumulated flux from both areas, i.e., two different cultivations in agricultural areas. A source area or footprint analysis was carried out to determine the area and the spatial distribution of the source strength which influences the fluxes measured

at the tower. The flux F measured at the coordinates (x_m, y_m, z_m) can be related to the footprint $f(x, y, z_m)$ by (e.g., [38, 39]):

$$F(x_m, y_m, z_m) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} Q(x', y') \cdot f(x' - x_m, y' - y_m, z_m) dx' dy' \quad (1)$$

Here, (x_m, y_m) are the horizontal coordinates of the tower and z_m is the measurement height. $Q(x', y')$ is the source strength (or surface flux) at (x', y'), given as g m^{-2} s^{-1}. The footprint (in m^{-2}) is factorized with $f_x(x, z_m)$ and describes the footprint in the mean wind direction x and a Gaussian distribution that describes the dependence on the lateral component y (e.g., [40]):

$$f(x, y, z_m) = \frac{f_x(x, z_m)}{\sqrt{2\pi}\sigma_y} \cdot \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \quad (2)$$

with $x = x' - x_m$, $y = y' - y_m$ and σ_y being the standard deviation of the lateral dispersion, which can be related to the standard deviation in the lateral wind fluctuations measured by the anemometer [21, 41]. The flux measured over a heterogeneous area with different land cover types is the sum of the surface fluxes F_i weighted by the corresponding footprint portion:

$$F(x_m, y_m, z_m) = \sum_{i=1}^{n} F_i \cdot \int_{Area(i)} f(x, y, z_m) dA = \sum_{i=1}^{n} F_i \cdot h_i \quad (3)$$

with

$$F_i = \int_{Area(i)} Q(x', y') dA \Big/ \int_{Area(i)} dA \quad i = 1, \dots, n \quad (4)$$

being the mean surface flux of the area with land cover type i, and

$$h_i = \int_{Area(i)} f(x, y, z_m) dA \approx \sum_{(x,y)\in Area(i)} f(x, y, z_m) \cdot \Delta A(x,y) \quad i = 1, \dots, n$$

$$(5)$$

being the dimensionless footprint portion of the land cover type i. The sum of all h_i, $i = 1, \dots, n$ equals unity. In order to determine the surface fluxes corresponding to the different land cover types, the footprint area is subdivided into grid elements $\Delta A(x, y)$ with (x, y) indicating the position of the grid elements. To each grid element is assigned a land cover type i. The integral is approximated by a sum over all grid elements which belong to the land cover type i. Since the flux tower is surrounded by two different cultivations, the number of land cover types $n = 2$. Consequently, there are two values for the footprint portions, h_1 for the maize field and h_2 for the soybean field, which obey the relationship $h_1 + h_2 = 1$.

In this study, the footprint calculations were made with an approximate analytical model [42], which computes the footprint at a horizontal coordinate x aligned with the mean wind direction. The model uses an explicit algebraic footprint expression and considers atmospheric stability, measurement height, and surface roughness within the surface layer. It is based on a hybrid approach that fits an analytic solution to results from a numerical stochastic Lagrangian dispersion model. The surface roughness of that field was used where the footprint had its maximum.

2.4 Spatial Partitioning of the Measured CO_2 Fluxes

The flux measured over two fields ($i=1, 2$) is given according to Eq. (3) by:

$$F_k = F_{1,k} \cdot h_{1,k} + F_{2,k} \cdot h_{2,k} \tag{6}$$

Here, k is the time index of a half-hour in the measurement period, which runs from $k=1$ to $N_t=10,848$ (226 days). F_k is the measured flux (in mg CO_2 m^{-2} s^{-1}) and the footprint portions $h_{1,k}$ and $h_{2,k}$ are known from the footprint analysis. The fluxes $F_{1,k}$ and $F_{2,k}$ in the maize and the soybean fields are unknown CO_2 fluxes. The surface fluxes depend on meteorological variables, such as solar radiation, temperature, humidity and other environmental variables such as phenological state, leaf area, metabolic velocity (photosynthesis and respiration rate) of each species cultivated. Equation (6) states that the temporal variation of the measured flux is caused by these environmental conditions which determine the fluxes $F_{1,k}$ and $F_{2,k}$, but also by the variables which determine the footprint. Our interest is to estimate the fluxes $F_{1,k}$ and $F_{2,k}$ in order to obtain for each field a complete CO_2 flux time series. To obtain the estimations of the fluxes on the maize field ($S_{1,k}$) and on the soybean field ($S_{2,k}$), a set of equations is formed:

$$F_\ell = S_{1,k} \cdot h_{1,\ell} + S_{2,k} \cdot h_{2,\ell} \tag{7}$$

There are N equations where the subset of N indices ℓ is a selection out of all half-hour indices. Those half-hours ℓ are selected for which measured fluxes are available and the meteorological conditions are similar to those at half-hour k (as will be described in the following section). In order to determine the optimal value of $S_{1,k}$ and of $S_{2,k}$ for the set of equations, a multiple regression analysis is applied. The multiple regression analysis is carried out for each half-hour k in the considered period. The NEE

of the entire period can then be estimated for the two land cover types $i=1, 2$ (maize and soybean) with:

$$NEE_i = \Delta t \cdot \sum_k S_{i,k} \tag{8}$$

where the fluxes of all half-hours k are summed up for the maize and the soybean field and where $\Delta t=1,800$ s.

2.5 Selection of the N Measurements

The multiple regression analysis is carried out with a set of measured fluxes which have been measured at similar meteorological conditions within a given time window that refers to the half-hour k. This means that a trend is imposed to the selected measurements in dependence on the footprint portions which is as much stronger the more the fluxes of the two fields differ (see Fig. 2). The measurements used in the regression analysis are selected according to a scheme (see Fig. 3), which has similarly been presented by Reichstein et al. [37] for the gap filling of missing CO_2 fluxes, not only for forest and scrubland sites, but also for agricultural sites. The therein described gap filling strategy bases on works by Falge et al. [43, 44] and has been evaluated positively by Moffat et al. [45]. As proposed by Reichstein et al. similar meteorological conditions are assumed to be present when the global radiation, the air temperature and the vapor pressure deficit do not deviate by more than 50 W m^{-2}, 2.5 °C, and 500 Pa, respectively, within a time window of ±7 days. If not enough measurements can be selected under these conditions then the requirements are eased according to the above mentioned scheme. The selection of the fluxes and its corresponding footprint portions is aborted when (a) the number of measurements is equal or greater than a minimum number N_{min} and when (b) the mean footprint portion is less than 0.95 in one of the fields. The first condition assures that the multiple regression analysis is carried out with a reasonable number N of equations. The second condition is used to avoid that the N footprints are all in the same field. If all footprints were in the same field, there is no information about the flux in the other field and the multiple regression would therefore not be possible. Since the multiple regression is carried out for all half-hours of the analyzed period the spatially partitioned fluxes $S_{1,k}$ and $S_{2,k}$ are not only calculated for the half-hours when measurements are available but also for those half-hours when CO_2 fluxes are missing. Thus the procedure carries out spatial partitioning as well as gap filling of fluxes.

2.6 Estimation of the NEE Error

In order to estimate the NEE error, i.e., the error of the sum of the flux series, we first consider the random error of the flux

Fig. 2 Schematic representation of gap filling in a homogeneous area (according to Reichstein et al. [37]) and of flux partitioning and gap filling in a heterogeneous area as presented in this study. The footprint portions $h_{1,k}$ and $h_{2,k}$ of the two fields impose a trend of the CO_2 fluxes which can be utilized to determine the fluxes on the two fields, $S_{1,k}$ and $S_{2,k}$
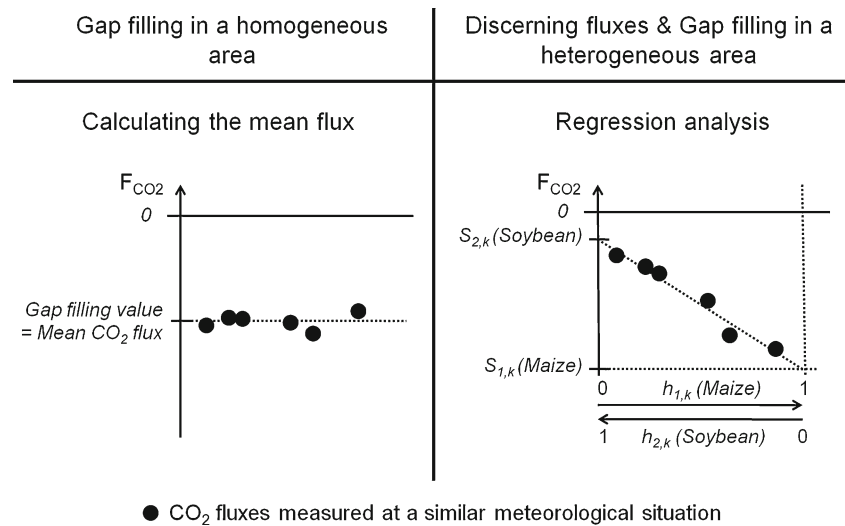
measurement, σ_r (see e.g., [36]). The determination of this standard deviation bases on differences between CO_2 fluxes measured on consecutive days, at the same time of the day and under similar environmental conditions of radiation, temperature and wind speed. In our analysis the wind direction has additionally been taken into account (difference in the footprint portions less than 0.05). Similar to an uncertainty analysis described by Richardson and Hollinger [46] for gap filling we then applied the spatial partitioning methodology 100 times. At each time random errors based on σ_r were added to the measured half-hour fluxes by using a double-exponential error distribution function. We obtain 100 NEE values, which are used to calculate the standard deviation, σ_{NEE}, and use the 2 σ_{NEE} value to indicate the NEE error.
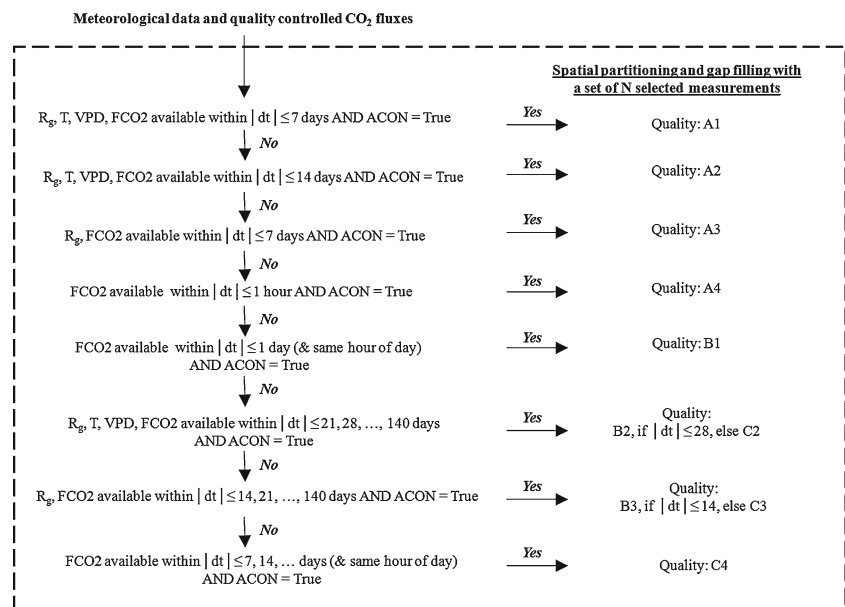
Further aspects of the uncertainty of the NEE values are addressed in the sections 3 and 4.

The scheme of the spatial flux partitioning methodology is shown in Fig. 4. The methodology has been implemented in a Geographical Information System (ArcGIS, Redlands, CA) which enables programming with Visual Basic and ArcObjects [47].

2.7 Test with Synthesized Fluxes

In order to verify the methodology two flux series were generated by using a non-rectangular hyperbolic light-response function [48] using parameter values given by Gilmanov et al. [49] and the measured radiation. The

Fig. 3 Flow diagram of the selection of measuremesampling fluxes used for the multiple regression analysis. Abbreviations *FCO2* CO_2 flux, R_g global radiation, *T* air temperature, *VPD* vapour pressure deficit, |*dt*| absolute difference in time. The condition ACON is true if the number of selected fluxes is equal or greater than a minimum number N_{min} and if the mean footprint portions are less than 0.95 for all land cover types. Quality of selection: *A*, high; *B*, medium; *C*, low
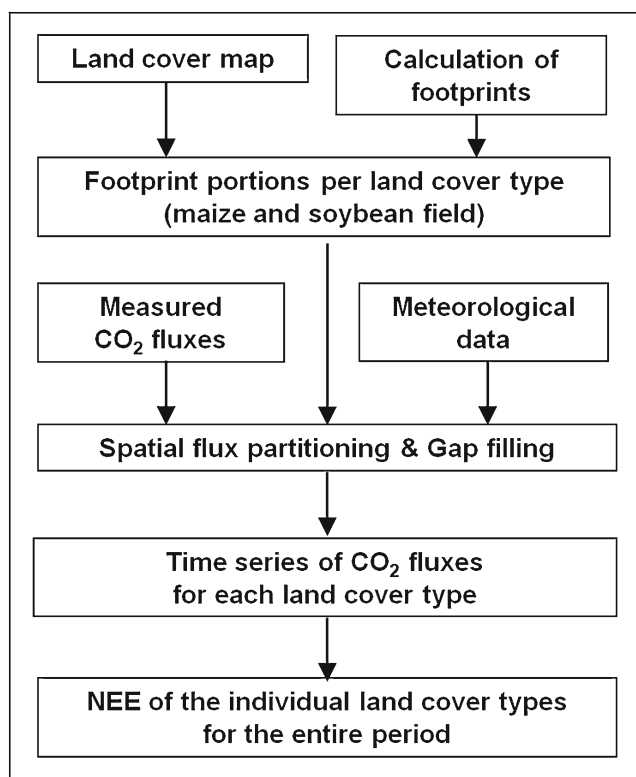
Fig. 4 Scheme of the procedure for partitioning measured CO_2 fluxes in a heterogeneous landscape (maize and soybean field) in order to determine the NEE of the individual land cover types
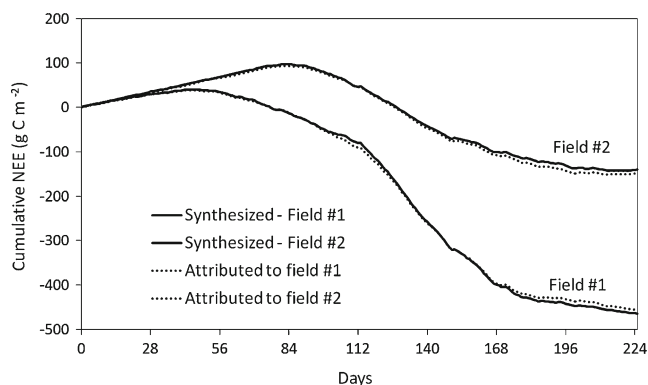

Fig. 5 Spatial flux partitioning of an aggregated flux data series. The data series is the sum of two synthesized flux data series weighted with its corresponding footprint portions; 40 % of the weighted fluxes was eliminated to simulate missing values. The figure shows the synthesized fluxes for both fields and the result of flux partitioning

Both examples demonstrate that there is a good agreement between the synthesized fluxes and the fluxes obtained by application of the presented methodology and that the calculated NEE errors do not underestimate the deviation of the calculated NEE from the NEE of the synthesized fluxes.

3 Results

3.1 Net Ecosystem Exchange Before the Growing Season

After the previous harvest of soybean (on both fields, on April 15, 2011) the dominating process was respiration with NEE values between 3 and 4 g C m^{-2} per day. Weeds began then to grow on the uncultivated fields, so that in early June the assimilation of CO_2 exceeded the respiration. In July and until mid-August the NEE was approximately −2 g C m^{-2} per day. On August 15, 2011 an herbicide was applied to remove the weeds. As a consequence in early September the NEE adopted again positive values. The spatial flux partitioning has not been carried out for the fluxes measured in this period because of the same vegetation on both fields and because of two longer measurement gaps (12 days in May/June and the last 20 days in August). Based on the available measured fluxes we estimated a NEE for the wintertime period, from April 16 until August 31, 2011, of 65 g C m^{-2}. Due to the longer gaps this value is associated with some uncertainty.

3.2 Footprint During the Growing Season

The footprint portions were calculated for each half-hour between September 1, 2011 and April 13, 2012. The point of maximum contribution of the footprint was at a distance of up to 150 m in 98 % of the footprints to the tower and the distance including 80 % of the footprint value was mostly less than 400 m. The measured fluxes can therefore be considered as

calculated fluxes were weighted by trapezoidal functions in order to simulate growth and senescence of the plants. Moreover, a random error was added to the fluxes by using a double-exponential probability density function [36, 50] with a standard deviation of 0.1 mg CO_2 m^{-2} s^{-1}. For each half-hour the two flux values were multiplied with corresponding footprint portions in order to obtain a CO_2 flux that is considered as the measured flux. The simulation period has the same length as the period of flux partitioning (226 days) and 40 % of the calculated fluxes were eliminated to simulate missing flux data. This flux series with gaps and the footprint portions serve as input for the multiple regression analysis. The two spatially partitioned series of fluxes, which are the output of the regression analysis, can then be compared with the two synthesized flux time series (see accumulated fluxes in Fig. 5). The sums of the synthesized fluxes are −464 and −140 g C m^{-2} for the first and second field, respectively. The application of the spatial partitioning leads to fluxes of −455±26 and −147±27 g C m^{-2}. The coefficient of determination R^2 is 0.87 for the first half-hour time series and 0.85 for the second half-hour time series. In a further test we assumed that there are no CO_2 fluxes at all in the area of the second field (e.g., an asphalted area). We obtain −456±26 g C m^{-2} for the first field and −6±27 g C m^{-2} for the second area. The accumulated daily fluxes for the second field never deviate from the zero-line by more than 11 g C m^{-2} (data not shown).

predominantly caused by the two fields, since other vegetation is beyond these distances. The prevailing wind direction was from northwest to south during daytime as well as during nighttime. Due to this preference in wind direction, the wind came from the maize field in 33 % of the half-hours, and consequently, the wind came from the soybean field in 67 % of the half-hours. In 70 % of the half-hours, either $h_{1,k}$ or $h_{2,k}$ were greater than 0.95. This indicates that the decrease in the footprint in lateral direction is so strong that the footprint portions depend more on the wind direction than on the lateral footprint distribution.

The CO_2 flux differences between both fields become obvious when the fluxes are compared for 3 days of December. On December, 10 and 11 the wind came predominantly from the maize field and on December, 12 from the soybean field. Although the meteorological conditions on December 10 and 12 days were similar (maxima of integrated global radiation 33.5 and 34.6 MJ m^{-2}, respectively), the temporal courses of the CO_2 flux were noticeably different, with stronger fluxes in the maize field (Fig. 6). This example already indicates that in December 2011 the CO_2 sequestration of the maize field was stronger than that of the soybean field.

3.3 Net Ecosystem Exchange in the Growing Season 2011/2012

The spatial flux partitioning, carried out with the data from September 1, 2011 to April 13, 2012 (226 days) leads to a
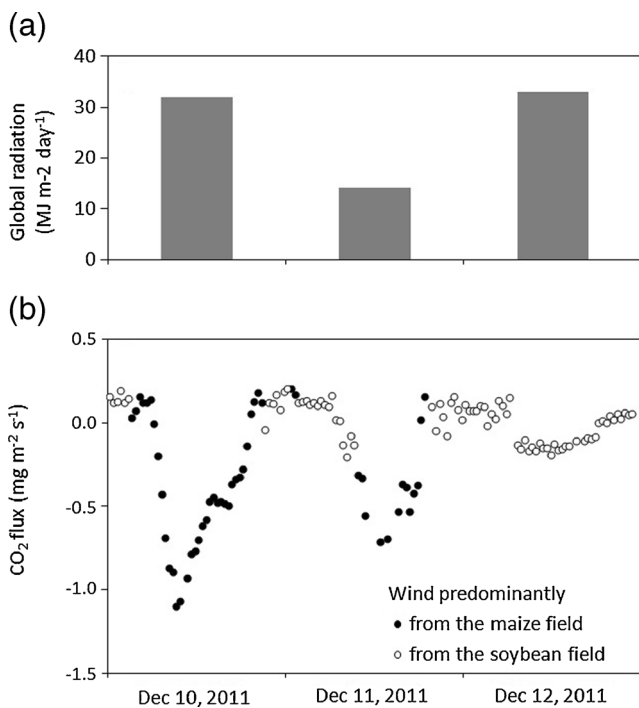

Fig. 6 **a** Total global radiation at three summer days in Mercedes, Argentina, and **b** temporal course of the CO_2 flux on the 3 days. The *filled* and *open circles* represent fluxes measured at wind directions predominantly from the maize field and the soybean field, respectively

half-hour time series of CO_2 fluxes for the maize and the soybean field. The spatially partitioned fluxes, multiplied by the corresponding footprint portions can be compared with the measured fluxes (see Fig. 7). The deviations of the data points from the 1:1 line are a measure of the flux partitioning uncertainty at the half-hour time scale. The root mean square error is 0.15 mg CO_2 m^{-2} s^{-1}, the mean deviation is only 0.8 μg CO_2 m^{-2} s^{-1}. The random error of the half-hour flux, σ_r, calculated as described in section 2.5, accounts for 0.10 mg CO_2 m^{-2} s^{-1}.

Exemplary time courses of the partitioned CO_2 fluxes are shown for different days in Fig. 8. The maximum of the CO_2 flux magnitude on the soybean field in the course of the day is around 1.5 mg CO_2 m^{-2} s^{-1}, a value which is similar to those found in other studies [51, 52]. The daily fluxes, shown in Fig. 9, exhibit a characteristic time course for each type of cultivation. Peaks which occur for some days in the series of the daily CO_2 fluxes are caused by low radiation due to cloudy sky and rainy weather. The strongest NEE was −8.9 g C m^{-2} day^{-1} for the maize field and −9.2 g C m^{-2} day^{-1} for the soybean field. The mean NEE error of the daily fluxes is 1.0 and 0.5 g C m^{-2} day^{-1}, respectively. The total sums for all 226 days accounted for −226± 48 g C m^{-2} for the maize field and −107±23 g C m^{-2} for the soybean field (± 2 σ_{NEE} error). The difference of the carbon uptake in this period, and consequently also in the complete agricultural cycle from harvest to harvest, accounts for 119± 58 g C m^{-2}. Soybean was sown 54 days after maize and therefore during a long time was measured the respiration of the uncultivated southeastern field. The NEE between sowing and harvest accounts for −240±48 g C m^{-2} (216 days) for the
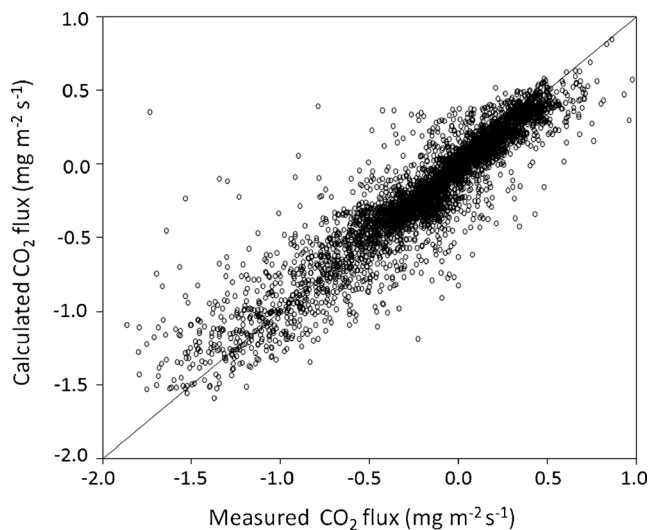

Fig. 7 Comparison of the measured CO_2 fluxes (F_k) with fluxes calculated by weighting the spatially partitioned flux on the maize and on the soybean field with the corresponding footprint portions ($h_{1,k}S_{1,k}+h_{2,k}S_{2,k}$). The deviation from the 1:1 *line* represents the noise caused by the application of the flux partitioning methodology at the half-hour level. The coefficient of determination (R^2) is 0.87, the root mean square error is 0.15 mg CO_2 m^{-2} s^{-1}, the mean deviation is 0.8 μg CO_2 m^{-2} s^{-1}
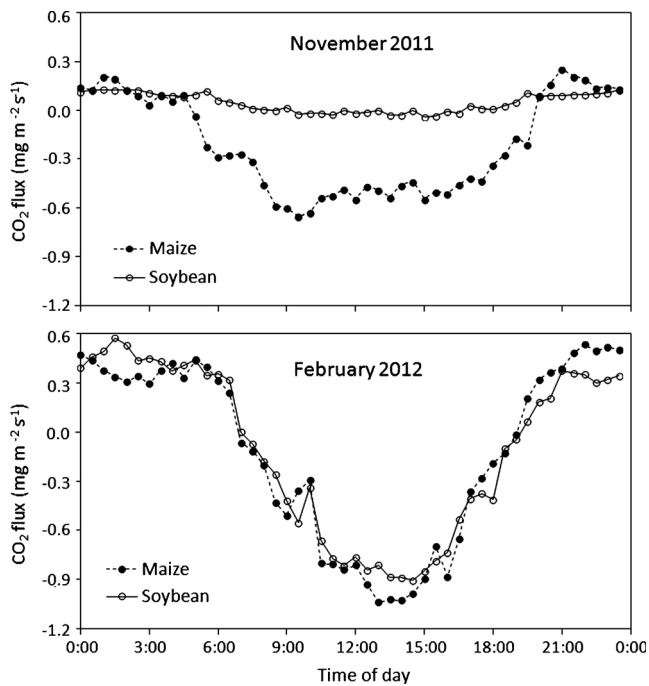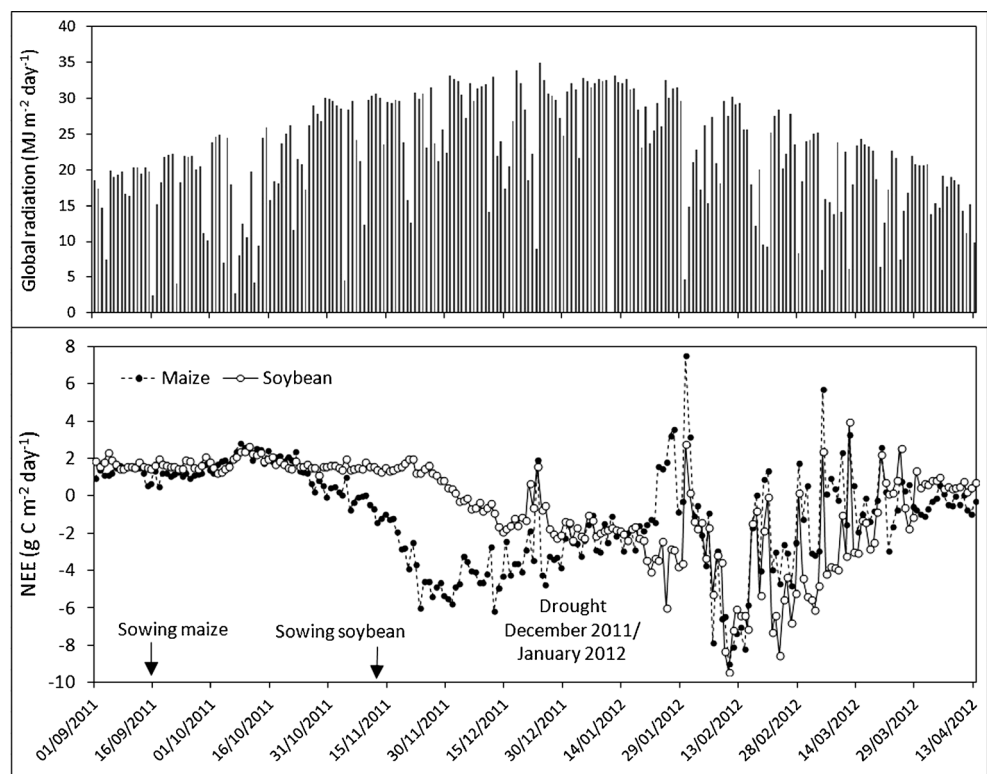
Fig. 8 Partitioning CO_2 fluxes averaged over a 7-day-period in November 2011 and in February 2012. In November, the maize field is growing, while the soybean has not yet been sown. In February, both fields show a similar CO_2 uptake

maize field and -231 ± 16 g C m^{-2} (154 days) for the soybean field. Therefore, during the respective growth cycles the mean daily carbon uptake on the soybean field has been higher

(NEE=-1.5 g C m^{-2} day^{-1}) than the mean daily carbon uptake on the maize field (NEE=-1.1 g C m^{-2} day^{-1}). The cumulative net carbon exchange of both fields is shown in Fig. 10.

4 Discussion

The presented methodology, which consists of a footprint model and a multiple regression analysis, allowed identifying the individual CO_2 fluxes of the two land cover types in an agricultural landscape. The methodology exploits the information given by all available fluxes, also of those fluxes which have been measured when the footprint covers different vegetation types. The flux partitioning methodology bases on fluxes which have been measured at similar meteorological conditions. In a homogeneous area the CO_2 fluxes would be similar. In a heterogeneous area however a trend is imposed—in dependence on the footprint portions—if the fluxes in the individual areas are different. With the presented methodology the strength of the dependence on the footprint portions is quantified which allows computing the CO_2 fluxes of individual areas. It should be noted that the methodology represents a framework with features that may be modified. For example, the footprint model may be replaced by another one, e.g., by one of those described by Schmid et al. [53] or developed by Kljun et al. [54] or other footprint models which take into account surface heterogeneities in complex terrains (e.g.,

Fig. 9 Spatially partitioned carbon fluxes per day on the maize field and on the soybean field during the measurement period, from September 01, 2011 until April 13, 2012. On the *top* is shown the integrated global radiation per day. Harvest took place on April 14, 2012 for soybean crop
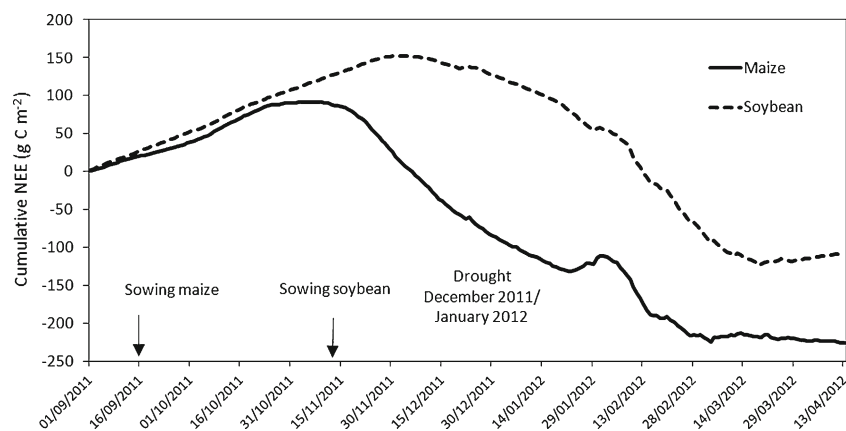
Fig. 10 Accumulated carbon assimilation on the maize field and on the soybean field during the measurement period, from September 01, 2011 until April 13, 2012

[55]). In our experimental set-up, the eddy covariance system has been installed at a relatively low height and the footprint portions are mainly determined by the wind direction. If the eddy covariance instruments are installed at tall towers in a pronouncedly heterogeneous area the footprint can be considerably larger than the size of, e.g., a single agricultural field and footprint modeling may demand higher requirements to obtain accurate values of the footprint portions. Another feature which may be modified is the scheme used to obtain measured CO_2 fluxes under similar conditions. In our study this scheme is strongly related to that given by Reichstein et al. [37].

The difference in the sowing times of maize and soybean is reflected in the daily CO_2 fluxes during October and November, when maize was already growing and soybean was not yet sown or in an early growth phase. This earlier development of maize made it more susceptible to the lack of water in the soil occurred during the first months. The rainfall recorded during September, October, November, and December was 11.8, 62.5 and 36.3, and 30.5 mm. In January, the rainfall was 103.5 mm and in February 140 mm. The decline of CO_2 assimilation of the maize field and the slow increase of CO_2 assimilation of the soybean field, see Figs. 9 and 10, can therefore be attributed to the drought. The precipitations registered during January and February have been closer to the mean long-time records and allowed the soybean plants to recover. This explains why from February 2012 on the CO_2 assimilation on the soybean field tends to be stronger than on the maize field. Without the drought we would have expected that maize as a C4 plant and a high biomass captures more CO_2 than soybean, as similarly has been found by Hollinger et al. [56]. The lowest CO_2 flux (i.e., the highest CO_2 uptake) registered for the maize field was -8.9 g C m^{-2} day^{-1}, similar to values found by Jans et al. [57]. Such strong flux rates could be observed only during 1 week. A substantial biomass of maize plants was therefore not built up, with the consequence that the farmer did not harvest the maize field. The lowest daily CO_2 flux of the soybean field occurred in February and March 2012 during the maximum plant development and at maximum

canopy height, with values around -8 g C m^{-2} day^{-1}, which is a value similar to those shown by Hollinger et al. [56]. Later the soybean plants, and also the maize plants, entered into the senescence period, with the effect that about 3 weeks before harvest the fields did not any more sequestrate CO_2. Some sequestration found on the maize field was due to the appearance of green weeds that occupied the ground between dry maize plants.

The methodology of spatial flux partitioning has its best performance when the wind comes randomly from both fields. The more random the wind direction, the more information is available about the different fields. In a period of several days with the footprint in one of the field only, fluxes of the other field have to be used, which were measured beyond this period. In our study the wind came with higher frequency from the soybean field. The longest period with no footprint in the maize field occurred in October 2011 and lasted 4 days. Therefore, in this case measured fluxes beyond this period had to be used to determine the CO_2 flux for the maize field. The higher NEE error of the northwestern field can be attributed to the fact that the wind came less frequently from this field, so that there is less information about the fluxes in this field available which could be used for the spatial flux partitioning. The advantage of the application of the footprint is that even when the footprint maximum is in one of the field, the information given by the measured flux can also used for the other field if the footprint is partially in this other field.

The error estimation described in section 2.5 treats the errors associated with the applied methodology. It does not consider systematic errors which may be associated with, e.g., a different footprint modeling, different correction methods of the eddy covariance data or different specifications of the conditions, under which flux data are eliminated from the time series. Based on the comparison of measured and calculated half-hourly fluxes (see Fig. 7), the mean of the deviations can be calculated which turns out to be quite small. The small bias of the calculated weighted fluxes is a hint that the unknown and not directly accessible biases of the two individual NEE are not very large. The standard deviation of the random error of flux measurement is in the range of those reported

elsewhere for agricultural sites [50]. In order to obtain the NEE complete agricultural cycle from harvest to harvest, i.e., between April 16, 2011 and April 13, 2012 (364 days), we sum up the NEE of the winter period 2011 and of the period for which the spatial flux partitioning has been carried out and obtain thus NEE values of -161 and -42 g C m^{-2} for the northwestern field (maize cultivation 2011/2012) and the southeastern field (soybean cultivation 2011/2012), respectively.

There are different approaches to attribute measured fluxes to the land cover types in a heterogeneous study area. An approach is to calculate the footprint in order to determine the land cover which controls most the measured fluxes. A simplification of this approach in suitable study areas is to classify the fluxes according to wind direction sectors, where each sector corresponds to a land cover type, and to calculate the mean diurnal course for each sector. This sector approach has been applied by Rogiers et al. [24] to attribute CO_2 fluxes in a complex terrain with meadow and pasture as predominant land covers. The sector approach avoids the application of a footprint model and the consideration of the underlying assumptions for the footprint calculation, but dependent on the wind direction a misclassification of the fluxes may be introduced [24]. Yet another approach is the combination of footprint models with photosynthesis and respiration models. Such an approach has been applied by Aubinet et al. [58], for a heterogeneous forest with beech and fir forests, and by Fox et al. [22], for a heterogeneous arctic tundra with different vegetation. This approach bases on ecosystem models for which a parameter adaptation is needed so that the models can describe the diurnal and long-term variation of the CO_2 fluxes. Detto et al. [21] used a similar approach for sensible and latent heat fluxes. They applied models for the sensible and latent heat fluxes, for each land cover type separately, and the weighted modeled fluxes were compared with measured values. As in this footprint/ecosystem model approach, our methodology uses a footprint model, but unlike this approach, our methodology does not require an ecosystem model.

The methodology of spatial flux partitioning could be validated ideally by a comparison with three eddy covariance systems (a second tower on the maize field and a third one on the soybean field). This would however require a costly experimental set-up, which in the present study has not been possible. Instead we used synthesized flux data with known input and output under similar environmental and experimental conditions (radiation and number of gaps) to assess the performance of the methodology. The good agreement which is achieved with the tests of the synthesized flux series confirmed a reliable quality of the spatial flux partitioning methodology. The reliability of the methodology is also supported by the two very plausible CO_2 flux series of maize and soybean which are closely related to the growth and phenological stages of the cultivations.

5 Conclusions

The increasing proportion of agricultural lands worldwide makes it necessary to intensify the research concerning the carbon exchange at agricultural sites. Eddy covariance measurements, when carried out with flux towers in a heterogeneous area, pose the problem to attribute the measured flux to the different land covers in the area. The problem arose for an agricultural landscape in Argentina, where the flux tower was placed between two fields with different cultivations (maize and soybean), and the objective has been to determine the NEE of both fields during the whole growing season. The result of a proposed methodology in this work, consisting of a footprint model and multiple regression analysis, are two time series of the NEE, each for one field. These spatially partitioned flux time series are noticeably different, what is explainable by the different sowing times and the growth stages of the maize and soybean plants. The time series exhibit furthermore the effect of a 2-month lasting drought on the two cultivations. Both fields are carbon sinks if the export of carbon by the harvest is not taken into account. In the complete agricultural cycle (from harvest to harvest, in this study 364 days) the carbon uptake in the field with maize cultivation in 2011/2012 has been higher than the carbon uptake in the field with soybean cultivation by approximately 119 g C m^{-2} due to the longer duration of the growing of maize. On the basis of the plausible flux time series and tests with synthesized data, we conclude that the presented methodology is an appropriate tool to identify the individual CO_2 fluxes of two land cover types in an agricultural landscape and may be extendable to other even more heterogeneous landscapes. In future works it may be fruitful to compare results of the presented methodology with those of other approaches that aim at attributing measured CO_2 fluxes to areas with different land cover.

References

1. Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A. S., Martin, P. H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grünwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., & Vesala, T.

(2000). Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology. *Advances in Ecological Research, 30*, 113–175.

2. Lee, X., Massman, W., & Law, B. (Eds.). (2004). *Handbook of micrometeorology: a guide for surface flux measurement and analysis*. Dordrecht: Kluwer Academic Publishers.

3. Aubinet, M., Vesala, T., & Papale, D. (Eds.). (2012). *Eddy covariance. A practical guide to measurement and data analysis*. New York: Springer Science+Business Media.

4. Baldocchi, D. D., Falge, E., Gu, L., Olson, R., Hollinger, D. Y., Running, S. W., Anthoni, P., Bernhofer, C., Davis, K. J., Evans, R., Fuentes, J., Goldstein, A., Katul, G., Law, B. E., Lee, X., Malhi, Y., Meyers, T. P., Munger, J. W., Oechel, W. C., Paw U, K. T., Pilegaard, K., Schmid, H. P., Valentini, R., Verma, S., Vesala, T., Wilson, K. B., & Wofsy, S. C. (2001). FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor and energy flux densities. *Bulletin of the American Meteorological Society, 82*, 2415–2434.

5. Canadell, J. G., Mooney, H. A., Baldocchi, D. D., Berry, J. A., Ehleringer, J. R., Field, C. B., Gower, S. T., Hollinger, D. Y., Hunt, J. E., Jackson, R. B., Running, S. W., Shaver, G. R., Steffen, W., Trumbore, S. E., Valentini, R., & Bond, B. Y. (2000). Carbon metabolism of terrestrial biosphere. *Ecosystems, 3*, 115–130.

6. Ciais, P., Canadell, J. G., Luyssaert, S., Chevallier, F., Shvidenko, A., Poussi, Z., Jonas, M., Peylin, P., King, A. W., Schulze, E. D., Piao, S., Rödenbeck, C., Peters, W., & Bréon, F. M. (2010). Can we reconcile atmospheric estimates of Northern terrestrial carbon sink with land-based accounting? *Current Opinion in Environmental Sustainability, 2*, 225–230.

7. Alberti, G., Delle Vedove, G., Zuliani, M., Peressotti, A., Castaldi, S., & Zerbi, G. (2010). Changes in CO_2 emissions after crop conversion from continuous maize to alfalfa. *Agriculture, Ecosystems and Environment, 136*, 139–147.

8. Li, L., Vuichard, N., Viovy, N., Ciais, P., Ceschia, E., Jans, W., Wattenbach, M., Béziat, P., Gruenwald, T., Lehuger, S., & Bernhofer, C. (2011). Importance of crop varieties and management practices: evaluation of a process-based model for simulating CO_2 and H_2O fluxes at five European maize (*Zea mays* L.) sites. *Biogeosciences Discussions, 8*, 2913–2955.

9. Smith, P. C., De Noblet-Ducoudré, N., Ciais, P., Peylin, P., Viovy, N., Meurdesoif, Y., & Bondeau, A. (2010). European-wide simulations of present croplands using an improved terrestrial biosphere model, Part 1: phenology and productivity. *Journal of Geophysical Research—Biogeosciences, 115*, G01014. doi:10.1029/2008JG000800.

10. Wang, Z., Xiao, X., & Yan, X. (2010). Modeling gross primary production of maize cropland and degraded grassland in northern China. *Agricultural and Forest Meteorology, 150*, 1160–1167.

11. Lal, R., Kimble, J. M., Follett, R. F., & Stewart, B. A. (Eds.). (1998). *Soil processes and the carbon cycle*. Boca Raton: CRC Press.

12. Verma, S. B., Dobermann, A., Cassman, K. G., Walters, D. T., Knops, J. M., Arkebauer, T. J., Suyker, A. E., Burba, G. G., Amos, B., & Yang, H. (2005). Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems. *Agricultural and Forest Meteorology, 131*, 77–96.

13. Baker, J. M., & Griffis, T. J. (2005). Examining strategies to improve the carbon balance of corn/soybean Agriculture using eddy covariance and mass balance techniques. *Agricultural and Forest Meteorology, 128*, 163–177.

14. Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., & Smith, J. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B, 363*, 789–813.

15. Edgerton, M. D. (2009). Increasing crop productivity to meet global needs for feed, food and fuel. *Plant Physiology, 149*, 7–13.

16. Baldocchi, D. D. (2003). Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. *Global Change Biology, 9*, 479–492.

17. Barcza, Z., Kern, A., Haszpra, L., & Kljun, N. (2009). Spatial representativeness of tall tower eddy covariance measurements using remote sensing and footprint analysis. *Agricultural and Forest Meteorology, 149*, 795–807.

18. Haszpra, L., Barcza, Z., Davis, K. J., & Tarczay, K. (2005). Long-term tall tower carbon dioxide flux monitoring over an area of mixed vegetation. *Agricultural and Forest Meteorology, 132*, 58–77.

19. Kim, J., Guo, Q., Baldocchi, D. D., Leclerc, M. Y., Xu, L., & Schmid, H. P. (2006). Upscaling fluxes from tower to landscape: overlaying flux footprints on high-resolution (IKONOS) images of vegetation cover. *Agricultural and Forest Meteorology, 136*, 132–146.

20. Soegaard, H., Jensen, N. O., Boegh, E., Hasager, C. B., Schelde, K., & Thomsen, A. (2003). Carbon dioxide exchange over agricultural landscape using eddy correlation and footprint modeling. *Agricultural and Forest Meteorology, 114*, 153–173.

21. Detto, M., Montaldo, N., Albertson, J. D., Mancini, M., & Katul, G. (2006). Soil moisture and vegetation controls on evapotranspiration in a heterogeneous Mediterranean ecosystem on Sardinia, Italy. *Water Resources Research, 42*, W08419. doi:10.1029/2005WR004693.

22. Fox, A. M., Huntley, B., Lloyd, C. R., Williams, M., & Baxter, R. (2008). Net ecosystem exchange over heterogeneous Arctic tundra: scaling between chamber and eddy covariance measurements. *Global Biogeochemical Cycles, 22*, GB2027. doi:10.1029/2007GB003027.

23. Kirby, S., Dobosy, R., Williamson, D., & Dumas, E. (2008). An aircraft-based data analysis method for discerning individual fluxes in a heterogeneous agricultural landscape. *Agricultural and Forest Meteorology, 148*, 481–489.

24. Rogiers, N., Eugster, W., Furger, M., & Siegwolf, R. (2005). Effect of land management on ecosystem carbon fluxes at a subalpine grassland site in the Swiss Alps. *Theoretical and Applied Climatology, 80*, 187–203.

25. González, J. A., & Calbó, J. (2002). Modelled and measured ratio of PAR to global radiation under cloudless skies. *Agricultural and Forest Meteorology, 110*, 319–325.

26. Langholz, L. H., & Häckel, H. (1985). Messungen der photosynthetisch aktiven Strahlung und Korrelationen mit der Globalstrahlung. *Meteorologische Rundschau, 38*, 75–82.

27. Vickers, D., & Mahrt, L. (1997). Quality control and flux sampling problems for tower and aircraft data. *Journal of Atmospheric and Oceanic Technology, 14*, 512–526.

28. Wilczak, J. M., Oncley, S. P., & Page, S. A. (2001). Sonic anemometer tilt correction algorithms. *Boundary-Layer Meteorology, 99*, 127–150.

29. Liu, H., Peters, G., & Foken, T. (2001). New equations for sonic temperature variance and buoyancy heat flux with an omnidirectional sonic anemometer. *Boundary-Layer Meteorology, 100*, 459–468.

30. Schotanus, P., Nieuwstadt, F. T. M., & DeBruin, H. A. R. (1983). Temperature measurement with a sonic anemometer and its application to heat and moisture fluxes. *Boundary-Layer Meteorology, 26*, 81–93.

31. Massman, W. J. (2000). A simple method for estimating frequency response corrections for eddy covariance systems. *Agricultural and Forest Meteorology, 104*, 185–198.

32. Massman, W., & Clement, R. (2004). Uncertainty in eddy covariance flux estimates resulting from spectral attenuation. In X. Lee, W. J. Massman, & B. Law (Eds.), *Handbook of micrometeorology: A guide for surface flux measurement and analysis* (pp. 67–100). Dordrecht: Kluwer Academic Publishers.

33. Leuning, R. (2007). The correct form of the Webb, Pearman and Leuning equation for eddy fluxes of trace gases in steady and non-

steady state, horizontally homogeneous flows. *Boundary-Layer Meteorology, 123*, 263–267.

34. Webb, E. K., Pearman, G. I., & Leuning, R. (1980). Correction of flux measurements for density effects due to heat and water vapour transfer. *Quarterly Journal of the Royal Meteorological Society, 106*, 85–100.

35. Foken, T., & Wichura, B. (1996). Tools for quality assessment of surface-based flux measurements. *Agricultural and Forest Meteorology, 78*, 83–105.

36. Hollinger, D. Y., & Richardson, A. D. (2005). Uncertainty in eddy covariance measurements and its application to physiological models. *Tree Physiology, 25*, 873–885.

37. Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., & Valentini, R. (2005). On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. *Global Change Biology, 11*, 1424–1439.

38. Horst, T. W., & Weil, J. C. (1992). Footprint estimation for scalar flux measurements in the atmospheric surface layer. *Boundary-Layer Meteorology, 59*, 279–296.

39. Schmid, H. P. (1997). Experimental design for flux measurements: matching observations and fluxes. *Agricultural and Forest Meteorology, 87*, 179–200.

40. Horst, T. W., & Weil, J. C. (1994). How far is far enough? The fetch requirements for micrometeorological measurements of surface fluxes. *Journal of Atmospheric and Oceanic Technology, 11*, 1018–1025.

41. Eckman, R. M. (1994). Re-examination of empirically derived formulas for horizontal diffusion from surface sources. *Atmospheric Environment, 28*(2), 265–272.

42. Hsieh, C. I., Katul, G., & Chi, T. (2000). An approximate analytical model for footprint estimation of scalar fluxes in thermally stratified atmospheric flows. *Advances in Water Resources, 23*, 765–772.

43. Falge, E., Baldocchi, D., Olson, R., et al. (2001). Gap filling strategies for defensible annual sums of net ecosystem exchange. *Agricultural and Forest Meteorology, 107*, 43–69.

44. Falge, E., Baldocchi, D., Olson, R., et al. (2001). Gap filling strategies for long term energy flux data set. *Agricultural and Forest Meteorology, 107*, 71–77.

45. Moffat, A. M., Papale, D., Reichstein, M., Hollinger, D., Richardson, A. D., Barr, A. G., Beckstein, C., Braswell, B. H., Churkina, G., Desai, A. R., Falge, E., Gove, J. H., Heimann, M., Hui, D., Jarvis, A. J., Kattge, J., Noormets, A., & Stauch, V. (2007). Comprehensive comparison of gap-filling techniques for eddy covariance net carbon fluxes. *Agricultural and Forest Meteorology, 147*, 209–232.

46. Richardson, A. D., & Hollinger, D. Y. (2007). A method to estimate the additional uncertainty in gap-filled NEE resulting from long gaps in the CO_2 flux record. *Agricultural and Forest Meteorology, 147*, 199–208.

47. Chang, K.-T. (2008). *Programming ArcObjects with VBA* (2nd ed.). Boca Raton: CRC Press.

48. Thornley, J. H. M., & Johnson, I. R. (2002). *Plant and crop modelling: A mathematical approach to plant and crop physiology.* Caldwell: Blackburn Press.

49. Gilmanov, T. G., Aires, L., Barcza, Z., Baron, V. S., Belelli, L., Beringer, J., Billesbach, D., Bonal, D., Bradford, J., Ceschia, E., Cook, D., Corradi, C., Frank, A., Gianelle, D., Gimeno, C., Gruenwald, T., Guo, H., Hanan, N., Haszpra, L., Heilman, J., Jacobs, A., Jones, M. B., Johnson, D. A., Kiely, G., Li, S., Magliulo, V., Moors, E., Nagy, Z., Nasyrov, M., Owensby, C., Pinter, K., Pio, C., Reichstein, M., Sanz, M. J., Scott, R., Soussana, J. F., Stoy, P. C., Svejcar, T., Tuba, Z., & Zhou, G. (2010). Productivity, respiration, and light-response parameters of world grassland and agroecosystems derived from flux-tower measurements. *Rangeland Ecology and Management, 63*, 16–39. doi:10.2111/REM-D-09-00072.1.

50. Richardson, A. D., Hollinger, D. Y., Burba, G. G., Davis, K. J., Flanagan, L. B., Katul, G. G., Munger, J. W., Ricciuto, D. M., Stoy, P. C., Suyker, A. E., Verma, S. B., & Wofsy, S. C. (2006). A multi-site analysis of random error in tower-based measurements of carbon and energy fluxes. *Agricultural and Forest Meteorology, 136*, 1–18.

51. Posse, G., Richter, K., Corin, J. M., Lewczuk, N. A., Achkar, A., & Rebella, C. (2010). Carbon dioxide fluxes on a soybean field in Argentina: influence of crop growth stages. *The Open Agricultural Journal, 4*, 58–63.

52. Prueger, J. H., Hatfield, J. L., Parkin, T. B., Kustas, W. P., & Kaspar, T. C. (2004). Carbon dioxide dynamics during a growing season in Midwestern cropping systems. *Environmental Management, 33*(1), 330–343.

53. Schmid, H. P. (2002). Footprint modeling for vegetation atmosphere exchange studies: a review and perspective. *Agricultural and Forest Meteorology, 113*, 159–183.

54. Kljun, N., Calanca, P., Rotach, M. W., & Schmid, H. P. (2004). A simple parameterization for flux footprint predictions. *Boundary-Layer Meteorology, 112*, 503–523.

55. Vesala, T., Kljun, N., Rannik, Ü., Rinne, J., Sogachev, A., Markkanen, T., Sabelfeld, K., Foken, T., & Leclerc, M. Y. (2008). Flux and concentration footprint modelling: state of the art. *Agricultural and Forest Meteorology, 152*, 653–666.

56. Hollinger, S. E., Bernacchi, C. J., & Meyers, T. P. (2005). Carbon budget of mature no-till ecosystems in North Central Region of the United States. *Agricultural and Forest Meteorology, 130*, 59–69.

57. Jans, W. W. P., Jacobs, C. M. J., Kruijt, B., Elbers, J. A., Barendse, S., & Moors, E. J. (2010). Carbon exchange of a maize (*Zea mays* L.) crop: influence of phenology. *Agriculture Ecosystems and Environment, 139*, 316–324.

58. Aubinet, M., Heinesch, B., Perrin, D., & Moureaux, C. (2005). Discriminating net ecosystem exchange between different vegetation plots in a heterogeneous forest. *Agricultural and Forest Meteorology, 132*, 315–328.