Chapter 11: Eddy covariance measurements over crops

C. Moureaux¹, E. Ceschia², N. Arriga³, P. Beziat², W. Eugster⁴, W. L. Kutsch⁵, E. Pattey⁶

¹ University of Liege – Gembloux Agro-Bio Tech, Belgium
² Centre d’Etudes Spatiales de la BIOsphère (CESBIO), France
³ Di.S.A.F.Ri.- Università degli Studi della Tuscia, Italy
⁴ ETH Zurich - Dept. of Agricultural and Food Sciences - Institute of Agricultural Sciences, Switzerland
⁵ Johann Heinrich von Thünen Institute (vTI) - Institut for Agricultural Climate Research, Germany
⁶ ECORC - Agriculture and Agri-Food Canada, Canada

1. Introduction

Croplands are managed ecosystems with rapid development over the course of the growing season under nearly optimal growth conditions with respect to nutrient availability (fertilization), water availability (possible irrigation in dry conditions), competition (monocultures where herbicide and fungicides applications keep other competitors off the plot) and plant health (insecticides minimize herbivory by insects).

Seeding and harvest take place within a time span of a few months, most often less than 1 year. In warm climate, especially in the subtropic and tropic zone, 2 or even 3 crops and harvest cycles can be accomplished over one year.

Between the cropping periods, the soil could remain bare or covered with crop residues with a possible development of either crop regrowths or weeds. In other cases, a fallow crop could be seeded.

So, during a year, very different and contrasted conditions are observed on a specific crop field: from bare soil to the crop maximum development. This implies
large variations in canopy height, in canopy structure and in leaf and vegetation area index (LAI and VAI). As a consequence, the structure of the turbulence and the albedo evolves during the cropping period and large variations of heat and net CO$_2$ fluxes are measured above these ecosystems, including a sign reversal for CO$_2$ fluxes.

Another crop specificity is that planting and harvest dates depend both on crop species and pedoclimatic conditions of the field. For example, in Europe and North America, winter crops are usually seeded between September and December (see Eugster et al. 2010) while spring crops are planted around April-May (e.g., spring wheat, rapeseed, potato, maize, sunflower). Consequently, the active growth and high CO$_2$ assimilation rate periods vary according to the crop type as illustrated in Figure 1 for Belgian crops of a 4-year rotation. The duration of the intercrop off-season period depends on the crops succession and may range from a few weeks to several months. For monocropping the duration is relatively constant, while for crop rotation, it may vary. This is illustrated in Figure 2 for Belgian and German 4-year rotations. For both site, the periods between harvest and next seeding range from less than a month between spring crops and winter wheat crops to 8 or even 9 months when a winter wheat crop is followed by a spring crop.

During the period between seeding and harvest, the accumulated carbon in the biomass could reach high values, e.g., $0.810 \pm 0.311$ kg C m$^{-2}$ for shoot biomass of maize in Southwest of France (Béziat et al., 2009), $0.88 \pm 0.05$ kg C m$^{-2}$ and $1.01 \pm 0.09$ kg C m$^{-2}$ for total biomass of winter wheat and sugar beet in Belgium (Aubinet et al., 2009). The dry biomass of these last two crops is $2.6$ kg m$^{-2}$ and
1.97 kg m$^{-2}$ respectively (Moureaux et al., 2006 and 2008). For maize, reported values of shoot biomass ranged from 1.7 to 2.5 kg DM m$^{-2}$ in North America (Pattey et al., 2001; Suyker et al., 2004 and 2005).

The net CO$_2$ ecosystem exchange measured over crops with the eddy covariance technique could reach high daily values. Net assimilation fluxes between -9 and -13 g C m$^{-2}$ d$^{-1}$ were observed for winter wheat (Baldocchi 2003; Soegaard et al. 2003; Anthoni et al. 2004; Moureaux et al. 2008; Béziat et al. 2009). Similar values were reported for soybean (Hollinger et al. 2005), rapeseed (Béziat et al. 2009) and sugar beet (Moureaux et al. 2008). In North America, reported maximum net uptake values in maize crops reached from -18 to -20 g C m$^{-2}$ d$^{-1}$ (Pattey et al. 2001; Hollinger et al. 2005; Verma et al. 2005).

Another specific feature of crop ecosystems is the numbers of management practices: tillage, planting, applications of fertilizer, herbicides, fungicides, insecticides and eventually of chemical haulm remover, irrigation, harvest, etc. The management activities are largely influenced by the cultivated crops, the pedoclimatic conditions and the crop rotation (e.g., in Belgium, generally a non inversion tillage is carried out for a winter wheat crop after a potato crop). In addition to the impact of these practices on the ecosystem net CO$_2$ exchange, CO$_2$ are emitted by the machinery, which could affect CO$_2$ concentration and flux measurements.

In general, crop canopies have a more homogeneous spatial composition compared to either forest or grassland canopies. They are often located on flat or gently rolling topography and surrounded by other agricultural fields reducing
part of the potential issues that could affect flux measured over “natural” using the eddy covariance technique (see chapter X).

This chapter discusses the specificities of eddy covariance measurements performed over cultivated areas. It deals with the aspects of set up, measurements and data processing which are specific to the agroecosystem, while a more general presentation is provided in Chapters 1 to 9. Ancillary measurements required to interpret CO₂ fluxes during crop development, compare different crops, quantify the net ecosystem carbon balance (NECB) and assess the impacts of management practices are also presented in this chapter. Finally, we discuss recent development of flux measuring systems that can be deployed in subplots, in order to compare management practices and to quantify their impact on carbon fluxes and its budget.

2. Measurement system

2.1 Choice of the site and communication with the farmer

The challenge in measuring fluxes from croplands comes 1) from the potential interference between the management practices and the instruments and 2) from the rapid crop development that requires adjustment of the measuring height. The choice of a representative site is discussed in Chapter 1. In addition to these general aspects, site investigators have to establish a collaboration agreement with the land owner/ producer. This either formal or informal agreement should include the following aspects: 1) common agreement on the measurement site location 2) communication in a timely manner between the producer and the research staff of next management practice for
protecting/removing temporarily the equipment, 3) access to detailed information on the management practices for the research team, 4) potential compensation for destructive plant sampling (see Section 8), access to electricity, etc. Information on management practices need to be documented as they might impact the fluxes during and follow their implementation. This can also be done by the research staff that needs to go on site every one or two weeks for the maintenance of the measuring system.

2.2 Flux tower and meteorological station configuration

General criteria to position the tower on the site such as predominant wind direction, fetch and site homogeneity as discussed in Chapter 1 are also crucial for measurement in agricultural systems but some additional aspects have to be considered. One of which is the mast which represents an obstacle for the tractors. A way to reduce disruption is to establish the tower and station at the field border in such a way that they do not obstruct the work by the farmer, but still close enough to have most of the flux footprint in the field of interest Fig 1.e). If this is not feasible, farmer will have to adopt a smart driver strategy.

In response to the challenge of measuring intensively managed ecosystem, some investigators adopted a mobile measuring system rather than a permanent installation. The permanent system consists on a fixed mast supporting the eddy covariance system surrounded by the meteorological sensors in a fixed enclosure. In this configuration, the soil is not tilled under the mast and the area surrounding the installation is either not cultivated or is managed by hand. This configuration allows having soil sensors and equipment enclosures installed permanently. In addition, this type of installation allows continuous
measurements even during management practices giving the possibility to monitor the ecosystem responses right after their completion. However, as the equipped mast area is not cultivated in the same way as the rest of the field, it may become not representative of the rest of the field and create a chimney effect as described in Chapter 1. Soil temperature, moisture and heat flux as well as net radiation could be biased if located in this area. However, the unmanaged area can be minimized in such a way that the flux footprint area remains mostly unaffected. Soil sensors – at least the ones below the ploughing depth – can be installed elsewhere under the managed area as long as electrical cables are guided to the data logger at a depth below the ploughing depth. The same can also be recommended for the other cables such as power supply and connection wires that should be buried at a depth greater than the tillage depth but above the drains depth, in the case the field is drained.

A mobile or roving measurement system is often a less invasive solution. The eddy covariance system and the meteorological sensors could be fixed on light masts (e.g., tripods or guy-wired masts) which are installed in the crop field after seeding. However, the deep soil sensors could be installed before sowing. In this way, the whole field is cultivated and the crop is less disturbed. Nevertheless, the eddy covariance system and the meteorological sensors have to be removed before the harvest or other cultivation practices and reinstalled as soon as possible. As a consequence, the flux measurements will be interrupted and some key measurement periods will be missing. Moreover, the installation of soil sensors disturbs the soil profile. It is recommended to dig a hole to insert the sensors on an undisturbed side of the hole. A good contact between the soil and the sensors is required to ensure good quality measurements. The hole need to
be refilled by respecting the soil horizons. It might take several days, depending on soil texture and precipitation to get representative soil measurements.

Mixed configurations could also be considered using, for example, a fixed eddy covariance mast and weather station in combination with temporary soil and radiation sensors installed in the field.

2.3 Measurement height

Here again, the rapid development of the crops and more particularly its evolving height impacts the measurement height. How close can flux instruments be from the canopy? Several considerations need to be taken into account. The first one is the path-length between the transducers that determines the response to small-scale turbulence through line averaging the wind velocity along the path, especially at the low height of measurement as usually encountered in agricultural studies (Pattey et al., 2006). For a path-length of 0.1 m, at 0.5 m above d, a reduction of 5% in W variance is observed, while at 2.5 m, this reduction is less than 3% (Wamser et al., 1997). The second one is the sampling frequency that should be higher closer to the ground. Similarly, for the covariance determination high frequency underestimations occur for combination of high wind speed, and low measuring height. By using a threshold value of 5 for the normalized frequency (f Z-d/U; where f, the sampling frequency = 10 Hz, Z the measurement height in m, d the displacement height in m and U the horizontal wind velocity in m s\(^{-1}\)), underestimation of high-frequency will take place for the following conditions: at Z-d=0.5 m for U>1 m s\(^{-1}\), at Z-d=1.0 m for U>2 m s\(^{-1}\), at Z-d=1.5 m for U>3 m s\(^{-1}\), at Z-d = 2.0 m for U>4.5 m s\(^{-1}\) (Pattey et al., 2006, Table 1). By locating eddy covariance sensors within the inertial
sublayer (also called equilibrium boundary layer; See Chapter ??), near-field influence associated with roughness sublayer heterogeneity can be avoided. The inertial sublayer depth increases with the fetch and is a function of canopy architecture (Munroe and Oke, 1975). For a fetch of 200m, the inertial sublayer depth varies between 2.4 and 3.4 m with the canopy height of maize, while for a fetch of 100m, depth varies between 0.1 and 1.7m, which shows that the fetch is too limited in the latter case for monitoring fluxes over a maize field for the entire growing season (Pattey et al, 2006, Figure 4). The bottom of the inertial sublayer can be approximated as 1.66-2.16 Z. Since many agricultural crops are growing in dense and very homogeneous stands, the aerodynamic roughness of their surface is smaller than that of other vegetation types, and hence it is possible to position eddy covariance flux sensors closer to the vegetation canopy than what is normally done over other relatively short vegetation types like grassland or shrubland.

Moreover, the confounding effects of surroundings areas have to be minimized and this is relevant for crops since in some regions fields are limited in size. It is however less of a concern if the surrounding fields contain the same crop or one with a similar phenology, such that the division into individual fields is rather a logistical than a plant physiological issue. As discussed later in this chapter, the footprint area is related to the aerodynamical displacement and closer to the canopy the measurement system is, smaller is the footprint area. However, to obtain flux measurements representative of field areas, sensors have to remain in the limit of the inertial sublayer.
At some site, the measurement height is adapted according to the crop height, i.e., by means of a telescopic tower, or by vertically moving a horizontal boom with the instruments on a solid 3+ m mast. In this way, measurements are performed in the inertial sublayer and the footprint area is minimized.

2.4. Maintenance

Harvest and soil tillage during dry conditions could generate a lot of dust. In case of closed-path analyser, this dust could rapidly obstruct the filter at the inlet of airflow to the analyser. Furthermore, as the measurement systems over crops are quite close to the soil (generally less than 4 m) and as some agricultural sites may be located close to residential area, pollution could also rapidly block this filter, especially during winter. For this reason it is crucial to continuously control the filters (or monitor the air flow) and change them when dirty.

Similarly open-path analysers may suffer from dust deposits on the optical windows. Rain following such dust events may clean the optical windows under some circumstances, whereas in other cases manual cleaning is required.

Further complications are birds and rodents. Since cropland areas are often lacking natural elements for birds of prey (e.g., hedges, single trees), particularly in intensively managed croplands, birds tend to perch on the tallest element in the landscape, which often is the eddy covariance flux system. A T-pole next to the system which is taller than the system itself would help to solve this problem, but there have been reports within southern localities where more elaborate structures were needed to keep the birds away from scientific equipment. Rodents also may be present in crops and might chew wires or enter
in cabinets placed in the fields and defecate on electronic components. Steel wool could be placed around the wires and in all possible entries of the cabinets.

3. Flux calculation

The dynamic height variation of crops has an impact on co-ordinate rotations which are applied on the raw means and second moments. Therefore, the half-hourly 2D rotation is recommended for measurements over crops. First rotation aligns the co-ordinate system with the mean wind, second rotation accounts for the inclination of streamlines to yield zero mean vertical wind speed. The planar fit method for tilt-correction is not appropriate since it requires several weeks of measurement during which the setup-conditions remain constant. This is rarely the case when measuring above a crop.

4 Flux corrections

4.1. Storage term

In short ecosystems like croplands, the storage term is expected to be small compared to forest ecosystem and consequently is frequently computed on the basis of one single CO₂ concentration measurements at eddy covariance flux measurement height (Anthoni et al., 2004; Moureaux et al., 2006; Suyker et al., 2005; Verma et al., 2005; Wohlfahrt et al., 2005; Xu and Baldocchi, 2004; Beziat et al. 2009). The storage term estimated from the single point method was compared to a multiple point profile. by and . For low turbulent periods, Saito et al. (2005) reported a 22 % underestimation of the storage term with the single point method in comparison with a six point profile, while Moureaux et al. (2008) found a 6 % overestimation of the single point method during turbulent periods which suggest a limited impact of the single height method on turbulent half-
hourly data. Whenever half-hourly CO$_2$ flux are discussed, CO$_2$ storage flux should be taken into account. For longer-term integrals or at the annual time scale its effect becomes negligible as discussed in Chapter 5.

4.2. Night-time flux data screening
Micrometeorological techniques based on turbulent transfer frequently underestimate CO$_2$ fluxes during night-time conditions when turbulence is low. A filtering procedure is proposed in Chapter 5 for screening data into either windy or calm condition. Two selection criteria were proposed: one based on the friction velocity ($u^*$) and the other based on the standard deviation of the vertical wind speed ($\sigma_w$). Pattey et al. (2002) found that $\sigma_w$ was a more robust criterion, independent of the sonic anemometer head configuration. The threshold value allowing the filtering could be dependent on the crop species and on the presence or absence of the crop (Moureaux et al., 2008, Beziat et al., 2009).

Reichstein et al (2005) proposed an automatic method to determine the $u^*$ threshold applied every 3 months to take into account the phenology and canopy properties. However, a 3-month division is not the most adequate approach for crops. The year should be divided into management periods that are a function of seeding and harvest dates, as well as regrowth events. It could even be subdivided according to the intensity of crop development or soil tillage. However, the length of the different periods has to allow a reliable determination of the threshold. Béziat et al. (2009) defined crop functioning periods between the dates of sowing, maximum crop development, harvest and tillage and determined a $u^*$ threshold for each crop functioning period.
5. **Data gap filling**

Crop characteristics will influence the choice of adequate gap filling procedures which are extensively discussed in Chapter 6. Management practices such as harvest (especially when vegetation is still green) or tillage can cause abrupt changes in CO₂ fluxes over agro-ecosystems. Such events have to be the limits of the periods considered for the different gap filling methods (i.e. non-linear regressions, look-up table, mean diurnal variation).

The artificial neural networks gap filling method required to be trained by presenting their sets of input data (meteorological data) and the associated output data (e.g., NEE). The rapid crop growth or crop senescence and the consecutive NEE dynamic complicate the training phase. Furthermore, in the case of agricultural ecosystems with crop rotation, the cultivated crops are different from one year to the other and make the artificial neural networks gap filling method unusable.

6. **Footprint analysis**

The evolving crop roughness and height and the consequently evolving aerodynamical displacement height influence the footprint. The knowledge of the mean crop height is then essential to determine the footprint area at different times during the year. Fetch needs to be long enough to accommodate the footprint expansion at night.

7. **Cumulated carbon exchange**
Commonly, fluxes from eddy covariance measurements are integrated and compared over one year time. However, the calendar year is not adequate for crops.

In order to compare CO$_2$ fluxes of different crops, the integration period should start at seeding and finish either at harvest or prior to the next seeding. In several synthesis studies of European crops (Kutsch et al. 2010, Ceschia et al. 2010), the selected integration period ranged from early October to end of September. This includes sowing and harvest of the spring and winter studied crops. However, in this way, the C degradation of crop residues occurring after the harvest, i.e., during autumn, winter and even spring, will be included in the following crop period and the impact of this degradation will be attributed to the next crop. For spring crops, starting the integration period in the spring at sowing and finishing it prior to the next seeding allow including the initial residue degradation.

Therefore, the best approach to derive the cumulated fluxes or the carbon balance of crops rotations is to integrate from seeding to prior the next seeding of the crop rotation for the entire sequence of crop rotation, which normally means that the integration limits are not aligned with the Gregorian calendar. This allows taking into account the crop sequence, the impact of management practices and periods between harvest and seeding. This was performed for two years rotations in North America (maize/soybean) by Hollinger et al. (2005), Suyker et al. (2004, 2005) and Verma et al. (2005), for a Belgian 4-year rotation by Aubinet et al. (2009) and integrating six full crop rotations of different European agricultural sites by Kutsch et al. (2010).
8. Additional measurements

The need for supplemental measurements depends on the objectives of the research. However, the knowledge of the sowing, harvest and tillage dates, plant density, LAI and biomass distribution dynamics is important to understand the fluxes. Extensive sampling might be required to cover the flux footprint area. Recently digital colour photography was proposed to measure LAI from crops (Liu and Pattey, 2010) in addition to conventional approach. For crops comparisons, the produced biomass is a key element. In the frame of the carbon balance assessment, to compute either the net ecosystem carbon balance (NECB) or net biome productivity (NBP), the imported and exported biomasses have to be known.

In order to obtain reliable dry biomass assessment and the associated uncertainties, it is recommended to collect several samples in representative areas of the field. To follow closely the vegetation dynamics, sampling can be performed every week or two weeks in relation to the dynamics of the crop. The biomass of the various organs could be estimated by separating samples into, seeds/fruits, green and dead stems and leaves. Root biomass is very challenging to measure and carries a lot of uncertainty and for this it is usually not routinely measured.

The harvested biomass assessment by the farmer by weighting some of the wagons containing the exported part of the crop (i.e., grain) might not be very
accurate. An alternative way is to destructively measure the dry biomass to be exported (e.g., grain, shoot) right before the harvest. Another way is to assess total biomass before the harvest and crops residues remaining thereafter and to subtract them. Finally, yield monitor installed on board of the combine can also be used, provided they are calibrated. They offer the advantage to provide a yield map.

In any cases, attention should be paid to reduce the uncertainties on biomass sampling since uncertainties on those estimations might be bigger than uncertainties on other flux measurements (Béziat et al., 2009).

9. Future experimentations

The agricultural management practices are expected to impact the carbon fluxes and the carbon budget. In the frame of carbon mitigation opportunities, these practices have to be evaluated in term of C fluxes and budgets. An attractive way to compare the agricultural practices is to divide a crop area into subplots managed in different ways and use several EC masts (e.g., Pattey et al., 2006; Davis et al., 2010). By dividing the field in 3 equal sections and installing two EC masts at the boundaries, continuous flux measurements can be carried out to compare two management practices, one in the middle area and the other one in the end areas (Pattey et al., 2006). In order to reduce source areas of scalar fluxes, the flux systems may be placed as close as possible to the canopy top but there are technical and theoretical issues limiting the eddy flux - canopy top minimum distance (see section 2.3). In this frame, investigating how close to the displacement height agrometeorologists can locate the flux measuring system becomes a priority.
Limitations are linked both to the turbulence structure close to the canopy and to the characteristics of sensors used to evaluate turbulent exchange.

By keeping EC measurement height above the lower limit of the inertial sublayer the influence of local canopy elements can be avoided. The lower limit of the inertial sublayer would be, for homogeneous crop canopy, between 1.7 and 2.2 times the height of the canopy (Pattey et al., 2006).

In addition, there is a technical limitation due to the characteristic length scales of the sensors used to evaluate turbulent exchange. Indeed a distance of at least 10-15 times greater than the longer sensor path length has to be kept from the exchange surface to reduce spectral loss under 5%. For example, in the case of three-dimensional ultrasonic anemometers and close-path analysers, the path length of most used sensors for eddy covariance is about 15cm. In the case of open-path sensor, both the sensor path length and the separation between instruments have to be considered and then the length increase to about 30 cm.

Using instruments with small-size transducers and with higher sampling frequency should allow reducing the measurement height requirements.

If the possible problems mentioned above are not considered when deploying the eddy covariance systems very close to the canopy top (for example at distances comparable to the sensors path length), then this would in most cases result in a reduction in the measurements of sensible heat, latent heat and carbon dioxide fluxes compared to measurements obtained in the inertial sublayer. Experimental
test involving natural tracers release and comparison of results coming from
different technical setup should provide data that are presently missing to better
understand how far small scale fluxes can investigated with present technologies
and which are the most significant drawbacks when measuring fluxes very close
to the crop canopy top. Experiments involving multiple deployments of eddy-flux
systems at various heights above the crop canopy, could allow the
agrometeorologists to find suitable empirical corrections when placing systems in
the roughness sublayer. These experiments would also benefit the footprint
models, such as those based on large eddy simulations that need adequate
parameterization of small scale turbulent dynamics, to better predict the source
areas for scalar concentrations and fluxes.
Figure 1: Evolution of the daily net ecosystem exchange between sowing and harvest for 4 crops in Belgium (Lonzée site). The thin continuous and dotted lines correspond to winter wheat crops in 2005 and 2007. Sugar beet crop (2004) is represented by black full squares and seed potato crop (2006) by grey crosses.
Figure 2: Evolution of the net ecosystem exchange for rotation of 4 crops in Belgium (Lonzée site) and Germany (Gebesee site). R symbolises crop regrowth. Seedling (S) and harvest (H) are represented by thin black lines.
Fig. 1: Example of eddy covariance cropland sites: (a) portable lightweight towers where only the power outlet/battery box (white box above black PVC tube) is a fixed structure (CH-Oen2); (c) fixed position in the center of the field, where the crop inside the fence is managed by hand similarly to the main crop outside the fence (FR-Lam). The example or a rice paddy from Spain (b, d) shows that special planning will be necessary for sites that are seasonally flooded. Photo credits: Eugster (a), Carrara (b, d), Béziat (c).
References


Liu, J. and Pattey, E., 2010. Measuring Agricultural Crop Canopy Structural Descriptors using Digital Photography. Agricultural and Forest Meteorology, 150, 1485-1490. (GreenCropTracker software to process the color photos can be downloaded for free from Flintbox)


