Chapter 12
Eddy Covariance Measurements over Crops

Christine Moureaux, Eric Ceschia, Nicola Arriga, Pierre Béziat, Werner Eugster, Werner L. Kutsch, and Elizabeth Pattey

12.1 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).

C. Moureaux (✉)
Gembloux Agro-Bio Tech, University of Liege, Gembloux, Belgium
e-mail: christine.moureaux@ulg.ac.be

E. Ceschia • P. Béziat
Centre d'Etudes Spatiales de la BIOsphère (CESBIO), Toulouse, France
e-mail: Eric.ceschia@cesbio.cnes.fr

N. Arriga
DIBAF, University of Tuscia, Viterbo, Italy
e-mail: arriga@unitus.it

W. Eugster
Department of Agricultural and Food Sciences, Institute of Agricultural Sciences, ETH Zurich, Zurich, Switzerland
e-mail: werner.eugster@agrl.ethz.ch

W.L. Kutsch
Institute for Agricultural Climate Research, Johann Heinrich von Thünen Institute (vTI), Braunschweig, Germany
e-mail: werner.kutsch@vti.bund.de

E. Pattey
ECORC, Agriculture and Agri-Food Canada, Ottawa, Canada
e-mail: elizabeth.pattey@agr.gc.ca

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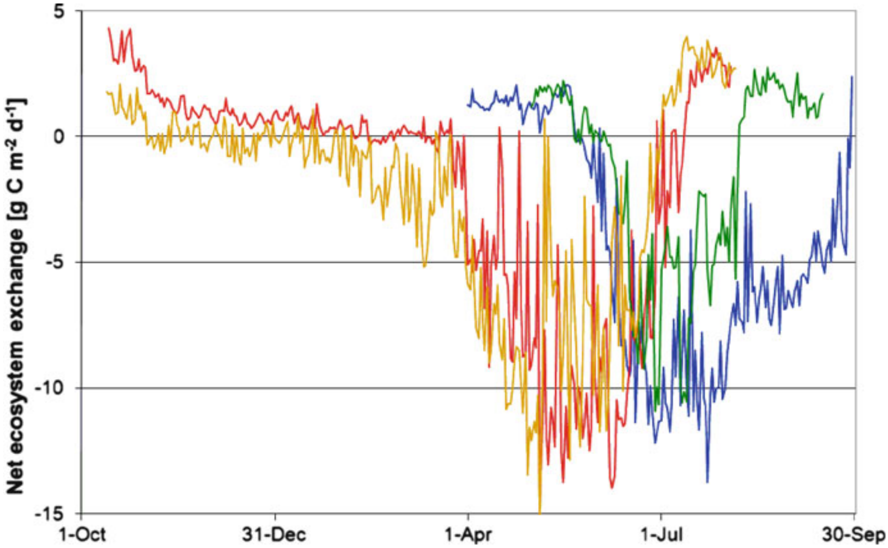

Fig. 12.1 Evolution of the daily net ecosystem exchange between sowing and harvest for four crops in Belgium (Lonzée site). The red and orange lines correspond to winter wheat crops in 2005 and 2007. Sugar beet crop (2004) is represented by the blue line and seed potato crop (2006) by the green line

Seeding and harvest take place within a time span of a few months, most often less than 1 year. In warm climates, especially in the subtropic and tropic zones, two or even three crops and harvest cycles can be accomplished over 1 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, canopy structure, leaf area index (LAI) and vegetation area index (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 Fig. 12.1 for Belgian crops of a 4-year rotation. The duration of the period between cropping seasons depends on the crop succession and may range from a few weeks to several months. For monocropping the duration is relatively constant, while for

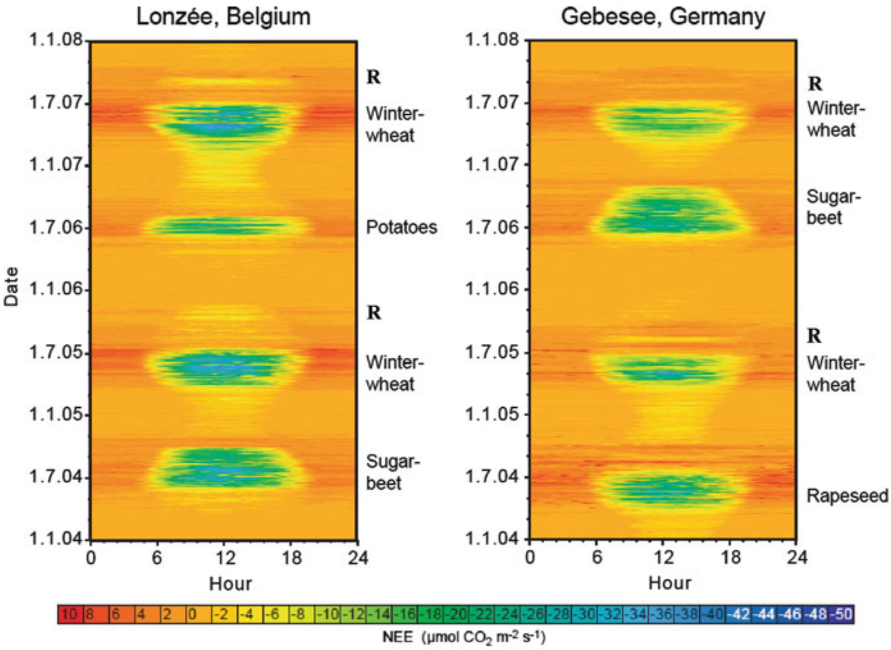

Fig. 12.2 Evolution of the net ecosystem exchange for rotation of four crops in Belgium (Lonzée site) and Germany (Gebesee site). R symbolizes crop regrowth

crop rotation, it may vary. This is illustrated in Fig. 12.2 for Belgian and German 4-year rotations. For both sites, the periods between harvest and next seeding range from less than one 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, for example, 0.810 ± 0.311 kg C m^{-2} for shoot biomass of maize in southwest of France (Béziat et al. 2009), 0.88 ± 0.05 kg C m^{-2} and 1.01 ± 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, 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, 2005).

The net CO_2 ecosystem exchange (NEE) measured over crops with the eddy covariance technique could reach high daily values. Net assimilation fluxes between -9 and -13 g C m^{-2} day^{-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. 2006). In North America, reported maximum net uptake values in maize crops reached -18 to -20 g C m^{-2} day^{-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 defoliant, 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 reduced tillage is carried out for a winter wheat crop after a potato crop). In addition to the impact of these practices on the NEE, CO_2 is 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" ecosystems using the eddy covariance technique.

This chapter discusses the specificities of eddy covariance measurements performed over cultivated areas. It deals with the aspects of setup, measurements, and data processing that are specific to the agroecosystems, while a more general presentation is provided in Chaps. 2–9. Ancillary measurements required to interpret CO_2 fluxes during crop development, to compare different crops, to quantify the net ecosystem carbon balance (NECB) and to 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.

12.2 Measurement System

12.2.1 Choice of the Site and Communication with the Farmer

The challenge in measuring fluxes from croplands comes from (1) the potential interference between the management practices and the instruments and (2) the rapid crop development. The choice of a representative site is discussed in Chap. 2. 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 when deemed necessary, (3) access to detailed information on the management practices for the research team, (4) potential compensation for destructive plant sampling (see Sect. 12.7), access to electricity, etc. Information on management practices need to be documented as they might impact the fluxes during and following their occurrence. This can also be done by the research staff that needs to go on site every 1 or 2 weeks for the maintenance of the measuring system.

12.2.2 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 Sect. 2.2.2.1, 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. If the tower is established within the field, farmer will have to adopt a smart driver strategy.

In response to the challenge of measuring an intensively managed ecosystem, some investigators adopted a mobile measuring system (Fig. 12.3a) rather than a permanent installation (Fig. 12.3b–d). The permanent system consists of 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

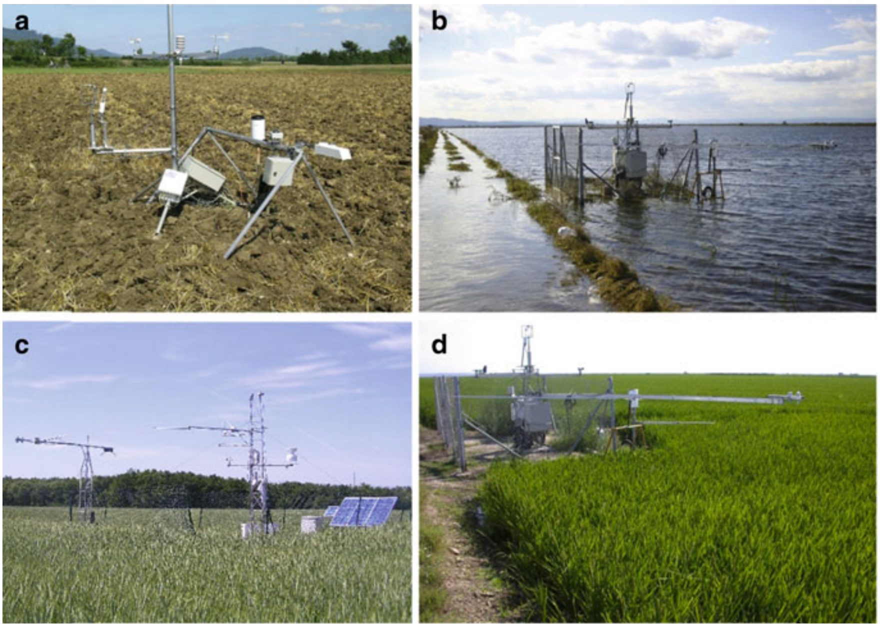

Fig. 12.3 Example of eddy covariance cropland sites: (**a**) portable lightweight towers where only the power outlet/battery box (white box above black PVC tube) is a fixed structure (CH-Oen2); (**c**) fixed position in the center of the field, where the crop inside the fence is managed by hand similarly to the main crop outside the fence (FR-Lam). The example of 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**))

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 can create a chimney effect as described in Sect. 2.2.1.2. 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 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. The hole needs to be refilled by respecting the soil horizons. A good contact between the soil and the sensors is required to ensure good quality measurements. 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.

12.2.3 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 the displacement height *d*, a reduction of 5% in vertical wind speed variance (σ_w) 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 (See Sect. 1.5.4).

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 ($f_s(h_m - d)/u$; where f_s, is the sampling frequency = 10 Hz, h_m 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 $h_m - d = 0.5$ m for $u > 1$ m s^{-1}, at $h_m - d = 1.0$ m for $u > 2$ m s^{-1}, at $h_m - d = 1.5$ m for $u > 3$ m s^{-1}, at $h_m - d = 2.0$ m for $u > 4.5$ m s^{-1} (Pattey et al. 2006). By locating eddy covariance sensors within the inertial sublayer (also called equilibrium boundary layer or well-mixed layer), 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 200 m, the inertial sublayer depth varies between 2.4 and 3.4 m with the canopy height of maize, while for a fetch of 100 m, depth varies between 0.1 and 1.7 m, 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). The bottom of the inertial sublayer can be approximated as 1.66–2.16 h_c (where h_c is the canopy height).

Moreover, the confounding effects of surrounding areas have to be minimized and this is relevant for crops since in some regions fields have limited 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. Moreover, similar adjacent fields contribute increasing the fetch and accommodate footprint increase at night. As discussed in Chap. 8 and later in this chapter, the footprint area is related to the aerodynamical displacement, and the closer to the canopy the measurement system is, the smaller is the footprint area (Sect. 8.3.2). However, to obtain flux measurements representative of field areas, sensors have to remain in the limit of the inertial sublayer.

At some sites, the measurement height is adapted according to the crop height, that is, by means of a telescopic tower, or by vertically moving a horizontal boom with the instruments on a solid mast. In this way, measurements are performed in the inertial sublayer and the footprint area is minimized.

12.2.4 Maintenance

Harvest and soil tillage during dry conditions could generate a lot of dust. In case of closed-path analyzer, this dust could rapidly obstruct the filter at the inlet of airflow to the analyzer. 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 analyzers 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.

12.3 Flux Calculation

The dynamic height variation of crops has an impact on coordinate rotations, which are applied on the raw means and second moments. Therefore, the half-hourly 2D rotation (See Sect. 3.2.4) is recommended for measurements over crops. First rotation aligns the coordinate system with the mean wind, second rotation accounts for the inclination of streamlines to yield zero mean vertical wind speed. The Planar Fit method (See Sect. 3.2.4.3) 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.

12.4 Flux Corrections

12.4.1 Storage Term

In short ecosystems like croplands, the storage term (F_C^{STO}, see Eqs. 1.24b and 1.25b) is expected to be small compared to forest ecosystem (Sect 2.5) and consequently is frequently computed on the basis of one single CO_2 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; Béziat et al. 2009). The storage term estimated from the single point method was compared to a multiple point profile. 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 suggests that the single height method could be used under turbulent conditions. Whenever half-hourly CO_2 fluxes are discussed, CO_2 storage flux should be taken into account.

12.4.2 Nighttime Flux Data Screening

Micrometeorological techniques based on turbulent transfer frequently underestimate CO_2 fluxes during nighttime conditions when turbulence is low. A filtering procedure is proposed in Sect. 5.3 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 (σ_w). Pattey et al. (2002) found that σ_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; Béziat et al. 2009).

For this reason the threshold in cropland should be calculated for the different management periods that are a function of seeding and harvest dates, as well as regrowth events. The year could even been 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_{*crit} threshold for each crop functioning period.

12.5 Data Gap Filling and Footprint Evaluation

Similar to the u_{*crit} determination, gap-filling (Chap. 6) and footprint evaluation (Chap. 8) in crop ecosystems require attention related to the fast or even abrupt changes in the ecosystem status due to rapid crop development and management practices.

12.6 Cumulated Carbon Exchange

Commonly, fluxes from eddy covariance measurements are integrated and compared over 1 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 carbon degradation of crop residues occurring after the harvest, that is, 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 crop 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 2-year 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).

12.7 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. Because of its influences on photosynthetic radiation interception, latent and sensible heat fluxes, LAI is important to measure over space and time. Recently, digital color photography was proposed to measure LAI from crops (Liu and Pattey 2010) in addition to conventional methods, since the approach is less limited by radiation conditions and the protocol can easily be implemented for extensive sampling. For crop 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 2 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 case, 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). In order to obtain reliable assessment of carbon inputs in case of organic manure application, several buckets of known area have to be placed on the field during the application and the carbon content of the collected samples has to be measured.

12.8 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 terms 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). In order to reduce source areas of scalar fluxes, while measuring "representative" data, the flux systems may be placed at the bottom of the inertial sublayer. If the flux measuring system is located in the roughness sublayer, flux measurement detects the near-field contribution, at the expenses of a more average contribution. Moreover, there are technical and theoretical issues limiting the eddy flux–canopy top minimum distance as discussed in Sect. 12.3. Using instruments with small-size transducers and with higher sampling frequency should allow reducing the measurement height requirements.

Experimental test involving natural tracers release and comparison of results coming from different technical setups should provide data that are presently missing to better understand how to perform small-scale fluxes with actual technologies and what are the most significant drawbacks when measuring fluxes at a short distance from the surface. 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.

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