Chapter 11
Eddy Covariance Measurements over Forests

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11.1 Introduction

In the 1970s, flux estimation over tall vegetation, like forests, using flux-gradient relationships were found impracticable (Raupach 1979). The roughness of the exchanging surface boosted turbulent mixing, reducing the concentration gradient and invalidating Monin-Obukhov similarity theory (Lenschow 1995). In the 1990s, the eddy covariance (EC) method was developed and turned out to be very promising for CO_2, latent, and sensible heat exchange quantification over these tall ecosystems. When the first networks of EC measurements were implemented (EuroFlux, Valentini et al. 2000; Ameriflux, Running et al. 1999), they included then a majority of forest sites. The other reasons for this historical forest leading position were their large terrestrial cover (FAO 2005 report) and their potentiality to store carbon over long periods (Valentini 2003).

EC over forest presents some particularities in (1) the methodology for flux computation, selection and determination of flux dependence, (2) the complementary measurements requested to interpret correctly the EC data, and (3) the interference created by ecosystem management. In this chapter, we propose to detail these different particularities.

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11.2 Flux Computation, Selection, and Dependence

11.2.1 Correction for High Frequency Losses

When closed-path infrared gas analyzers (IRGA) are used (Sect. 2.4.2), high-frequency fluctuations of the gas concentration is attenuated during tubing transport (Sect. 4.1.3.2). This provokes losses in the high-frequency component of the co-spectra, needing implementation of correction factors. The amplitude of these losses is principally linked to tube length, airflow rate, measurement height above the canopy surface, roughness of this surface, and wind conditions (Sect. 4.1.3.2).

In tall forests, the gas transfer may be very long (more than 30 m) as the closed-path analyzer cannot be installed near the sampling point but in a shelter close to the tower basis. On one hand, this configuration facilitates the frequent calibration operations when performed manually and improves the comfort when technical interventions are requested. On the other hand, the high-frequency losses and then the correction factors could become very significant, leading to large uncertainties. One way to reduce them is to hold a relatively large airflow rate in the tube. This requests electric power and could decrease the life span of the pumps. In this case, it is suggested to employ two or more pumps in serial with lower voltage than the nominal one. The installation of the IRGA at the top of the tower to reduce high-frequency losses and the impact of the correction factor is advisable when the injection of a calibration gas could be performed from the ground or driven by an automatic system.

As mentioned before, the high-frequency losses depend on the canopy surface roughness. So, for deciduous forests, the correction factor can vary between leafless and leafy periods. The difference has to be tested by determining this correction factor for each of these periods. Similarly, if during the measurement campaign the EC system height above the top of the forest is significantly reduced (due to significant tree growth), the eddy size viewed by the EC system is smaller, enhancing the high-frequency component of the co-spectra. The impact of high-frequency attenuation becomes more important. It is then recommended to reevaluate the correction factor. The possibility to lift up the EC system is another method to overcome this problem but it implies a new footprint analysis to certify that fluxes measured are still coming from the targeted ecosystem (Chap. 8).

11.2.2 Rotation Method

In forests, the support of the EC system is quasi-systematically a tower with a structure larger than masts that can be utilized for grasslands or crops (Sect. 2.2). The sonic anemometer has to be put aside from the tower using an arm with a length equivalent to two or three times the tower diameter (see Sect. 2.2.2.5) which may lead to sensor stability and horizontality problems. In addition, the presence of other measurement devices may constitute additional obstacles (other sensors, supplementary tower element, etc.). In these conditions, the distortion created in the wind streamline flow can have a significant impact and the choice of the Planar Fit Sector approach (Sect. 3.2.4.3) as rotation method becomes necessary.

11.2.3 Friction Velocity Threshold

When turbulence decreases, a significant part of the trace gas studied can be stored in the canopy air or migrate out by advection (Sect. 5.1.3, Aubinet et al. 2005). Then, EC system may underestimate the flux exchanged by the ecosystem. Measurements of vertical temperature or concentration profile (see Sect. 11.3.1) allow correcting EC data for storage but, presently, the only way to overcome advection problem is to apply u^* filtering (Sect. 5.3). The high density of some forest canopies, which reduces eddy penetration, combined with the large internal air space, can lead to relatively frequent and important storage and advection events. Consequently, the vertical profile should be determined with care (see Sect. 11.3.1) and the friction velocity threshold for data filtering ($u_{*\mathrm{crit}}$, see Sect. 5.3.2) could be high, leading to an important number of rejected data. This creates large gaps in the data sets covering up to 50% of the time (Papale et al. 2006). The accuracy of data gap filling method (Chap. 6) is then crucial for determining correctly the net exchange integrated over long periods (month, season, year).

11.2.4 Selection Based on Footprint

The choice of measurement height should be a trade-off between the necessity to reduce the high-frequency losses (Sect. 4.1.3.2) and those to delimit the footprint extent to measure fluxes mainly coming from the targeted ecosystem (Sect. 8.3.2). Unfortunately, in forests, the problem of access to the material (existence of platforms, supporting arms, etc.) can limit the possibilities in the choice of system height, giving sometimes non adequate positioning. Then it is important to perform footprint studies (Chap. 8) also as an additional tool for data screening and selection (Göckede et al. 2008). This procedure is also necessary when some plots need to be excluded from the accepted footprint area because they become very specific compared to the surrounding forest. This happens, for example, when the thinning is operated by different persons (different plot adjudications in state forests) leading to large spatial heterogeneity.

11.3 Additional Measurements

Some additional measurements to the EC fluxes are necessary to obtain the net ecosystem exchange, to partition it between its main components, and to interpret them. Beside the characterization of the climatic conditions (radiation, air temperature, humidity, etc.), soil efflux (topic is developed in details for CO_2 in Kutsch et al. 2010), and reflectance indexes (NDVI, PRI, see Grace et al. 2007), some of the complementary measurements have some specificities when they are performed on forests.

11.3.1 Vertical Profile of Concentration in Canopy Air

The quantification of storage in the canopy air can be necessary for some gases like CO_2 for better estimation of the half-hour NEE when turbulence is relatively low and ecosystem is tall. This situation is very usual in forests (up to half of the time, Longdoz et al. 2008) with tall trees and dense canopy that limit penetration of eddies. The storage is calculated as the difference between successive estimates of gas content in the air canopy, themselves calculated from vertical profile of concentration (Xu et al. 1999). This profile includes sampling levels not only in the free air below EC system but also in the soil, as CO_2 can also be stored in the soil pore air. In forests, the distance between the higher and lower sampling levels can be large when trees are tall. As gas concentration can change rapidly, all the levels of the profile have to be sampled within a short period in order to estimate accurately the total air canopy content. The fast purge of the different tubes is then performed by one large pump but it induces too large depression in the gas analyzer to correctly measure concentration. Consequently, another small pump should suck air from the main tube into the analyzer.

Vertical profile in soil pore air should be measured when gas concentrations have significant temporal fluctuations. In the forest, the number of sampled points in the soil (different depths) is larger than in the free air as concentration gradients are steeper because mixing processes are less active. Different methods have been tested to measure this gradient (Risk et al. 2002; Tang et al. 2003; Jassal et al. 2005). It seems that porous tubing (Gut et al. 1998) inserted horizontally and connected in close loops with gas analyzer gives the best results (Flechard et al. 2007), presenting the advantages of larger spatial representativeness and/or shorter response time and/or less expensive compared to other techniques (syringe sampling, sensors buried or located in vertical tube holed at the sampled depth).

11.3.2 Leaf Area Index

In contrast to crops, leaf area index (LAI) is relatively constant in forests during the growing season and its determination is essential to analyze interannual variability in fluxes. Different nondestructive methods exist (radiation transmission, LAI meters, litter collection, etc.; see Bréda 2003). Each of them present advantages and limitations and their combination remains the best way to have the more accurate and representative estimation. LAI estimated from radiation interception by canopies can be performed with permanent or moving sensors. One is located above the canopy and several are set below. Obviously, data have to be recorded simultaneously. The number of these sensors depends on the spatial heterogeneity of the canopy but ten is a minimum (Widlowski 2010). The same comment can be made about the number of hemispherical pictures. Optical methods do not require frequent visits at the studied forest but necessitate specific equipments (LAI meter, radiation sensors, etc.) and important assumption about the leaf angle distribution. This last can be estimated by various ways according to the species and tree density (Beta distribution function, ellipsoidal function, rotated-ellipsoidal function, Verhoef's algorithm, and de Wit's functions; see Wang et al. 2007). About the litter collection method, leaves or needles fallen in bags (could be hanged or laid on the soil and micro perforated to evacuate water) have to be brought back to laboratory for area (with an area meter) and dry mass determination. Collections have to be frequent to avoid leaves or needles decomposition in the bags and modification of their area and mass before measurement. This method is time consuming because of frequent site visits and of the large amount of leaves/needles to analyze with the area meter but it also gives quantitative information about the litter production biomass.

11.3.3 Biomass Estimates

When biomass increment and biomass carbon (or other element) content are known, they can be associated for comparison and validation of EC net ecosystem exchange (Granier et al. 2008). In forests, over medium-term periods (typically 1 year), when neglecting the variations of soil carbon content and wood carbon density, carbon sequestration estimated with EC can be compared to annual tree biomass increment. The latter takes into account estimates of mortality and exports (resulting from management, thinning or clear-cut) and temporal evolution of the whole trees and understory biomasses. Tree biomass is often estimated with allometric relationships from tree diameter at breadth height (DBH) and tree height (Van Laar and Akça 2007). The main source of uncertainty comes from the estimation of the belowground biomass but, more and more, root system excavations are performed with this goal (Peichl and Arain 2007), reducing this uncertainty for the most investigated tree species. The tree biomass estimation from DBH requires DBH inventories of a representative tree sample within the footprint area. This selection includes trees from different diameter classes and with different status (dominant, codominant, intermediate, suppressed) over the different soil types in the footprint area. In consequence, the number of trees selected can be large and thus the DBH manual measurement can be time-consuming, which explains the limited number of the campaigns (season to year). In addition, estimate of mortality (trees and branches) results also from important field campaigns and accuracy on exported wood quantity depends on information given by forest managers (see Sect. 11.4). Due to all these limitations, a relatively low number of forest sites can address the comparison between NEE and biomass increment (Granier et al. 2008). For example, it can be observed in Fig. 11.1 that at the end of the growing season for the

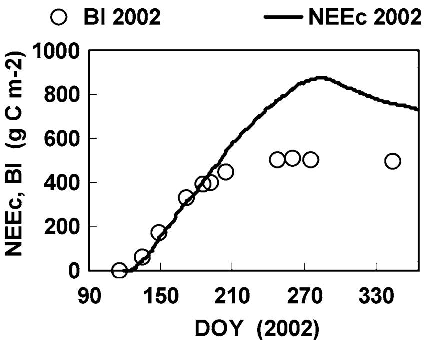

Fig. 11.1 Temporal variation of the cumulated net ecosystem exchange (NEEc) computed from EC data (*black line*) and carbon biomass increment (BI) estimated from successive DBH inventory campaigns at the Hesse forest (*open circles*) in 2002. The starting point of NEE is set at the beginning of radial tree growth (DOY 120)

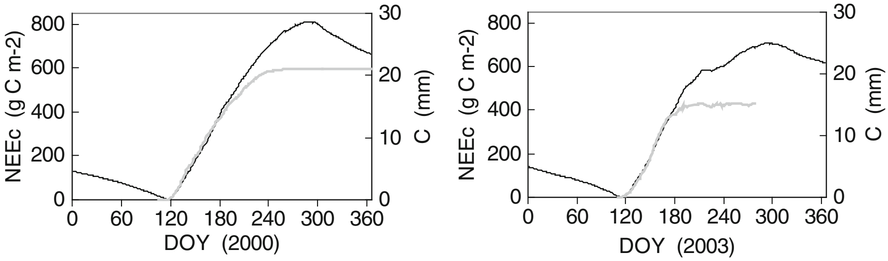

Fig. 11.2 Temporal variation of the cumulated net ecosystem exchange (NEEc) computed from the Hesse EC data (*black line*) and mean tree circumference (*gray line*) measured with dendrometer bands (up to steady state). The starting point of NEE is set at the beginning of radial tree growth (DOY 119)

Hesse forest (beech stand in the North-East of France), a deviation appears between the cumulated NEE, as estimated with EC data, and the biomass increment from manual tree growth measurements. Tree growth stops several weeks before that ecosystem turns from a CO_2 sink to a source. This deviation can be explained by the switch from structural carbon production to carbon storage (in sugars, starch, amino acids, lipids, etc.).

On shorter timescale (day, up to season), automatic dendrometer bands give the variation of tree diameter or circumference. For technical and cost reasons, dendrometer bands can be installed only on a small number of trees. The comparison of the estimated increase in biomass from dendrometer band measurement with EC carbon sequestration is, therefore, often only relative, but can bring very interesting results. Figure 11.2 shows that from 1 year to another this deviation occurs at different dates, due to different environmental conditions (an exceptional drought has been experimented by the Hesse forests in 2003). There is therefore an interannual variability in the amount of carbon stored in the trees that will impact the budburst date, LAI, and growth in the following year.

11.3.4 Sap Flow

Stand-scaled sap flow measurements can be compared to EC latent heat flux in order to separate transpiration from soil evaporation and understory transpiration, as the deviation between both fluxes can reach up to 25% of the total water vapor emission even in closed forests (Granier et al. 1996). The transpiration corresponds to the loss of water in the root zone and its determination is essential to complete the soil hydraulic balance. One of the most used methods for measuring sap flow, the heat dissipation (Granier method; Lu et al. 2004), has been developed for trees. Consequently, most of sap flow data sets concern forests.

When the objective is the estimation of transpiration at stand scale (on the footprint area), the maximal accuracy is obtained by measuring sap flow on the trees belonging to classes having the larger weight in the transpiration flux. The amount of sampled trees is a trade-off between the necessity to cover the heterogeneity in age, diameter, soil composition, foliage structure, and the restriction imposed by the material available. Most of the time, three tree status are considered (dominant, codominant, suppressed) and three (for suppressed) to five (for dominant) sap flow sensors are requested according to the status. The sap flow density of the stand (E_{SF}, m^3 of water $m^{-2}$of soil s^{-1}) is given by

$$E_{\mathrm{SF}} = \sum_i (u_{\mathrm{SF},i} \cdot A_{\mathrm{SF},i}) \qquad (11.1)$$

where the index i refers to tree classes, $u_{\mathrm{SF}i}$ is the sap flux density ($m^3$of water $m^{-2}$of sapwood s^{-1}), and $A_{\mathrm{SF}i}$ is the sapwood area (m^2 of sapwood $m^{-2}$of soil). This last can be estimated for each class by combining sapwood depth determination (from analysis of cores sampled in trunks) and DBH measurements.

11.3.5 Extractable Soil Water, Throughfall, and Stem Flow

Soil water content (SWC) in the root zone is an important factor regulating stomatal opening and then helps analyzing transpiration and carbon assimilation deduced from EC data (Granier et al. 2007). SWC is often expressed as relative water content (REW), varying between 0 and 1, corresponding to the ratio between the actual extractable soil water EW and the maximum extractable soil water EW_{max}. EW and EW_{max} are the difference between, respectively, actual or field capacity soil water contents and the permanent wilting point (−1.6 MPa). In forests, spatial variability of soil water and therefore of REW can be large. This variability is partly due to that of throughfall, consecutive to gaps in the foliage and to stem flow accumulation at trunk base. It can reach up to 30% of the incident precipitation for deciduous (Andre et al. 2011), but is generally lower for coniferous (Levia and Frost 2003). The experimental setup for soil water measurement at the plot level has to be designed to capture both temporal and spatial variability. Temporal variations are monitored using automatic sensors buried in the soil (often deducing SWC from measurement of soil dielectric constant by time or frequency domain reflectometry; see Prichard 2010) and installed at different depths. Those sensors have a fast response, but their installation necessitates digging trenches and/or holes in the soil leading to perturbations of the soil structure (layer mixing, compaction, creation of preferential flow chimney). Moreover, their small sampling volume (few tens to hundreds of cubic centimeters) limits the measurement of spatial variability. In the ideal situation, they are combined with movable systems used to perform measurements manually on a large number of locations at different depths. These systems use one probe circulating in vertical tubes inserted in the soil and able to measure SWC without direct contact with the soil (presence of the tube wall). Neutron probes and sticks with frequency domain reflectometry rings are the main systems employed (see Prichard 2010).

Measurements of throughfall and stem flow complete the water balance database (with incident precipitation and soil water content). The throughfall measurements are performed with collectors located at the ground level. When focusing on the short-term (hourly to daily) components of the water balance, the collectors have to be connected to automatic tipping buckets in order to be able to estimate the time lag with incident precipitation. These buckets should tip over for relatively low water amount (0.1 or 0.2 mm) as the throughfall quantity could be quite small in case of weak precipitation. The problem of the collector number required to cover the spatial heterogeneity is similar to one of the radiation interceptions by the canopy (see Sect. 11.3.2) and a minimum of ten is also recommended.

The stem flow collection is performed with channels stuck on the trunk and the water is driven into a rain gauge with automatic tipping buckets when short-term quantification is required. In this case and to overcome a too-rapid bucket filling (leading to non counted water losses), the volume of the buckets has to be larger than for throughfall. Indeed, even if stem flow is lower at minimum third time, the surface of interception (a tree canopy for stem flow compared to the collector surface for the throughfall) is about ten times larger.

11.3.6 Heat Storage

The ecosystem heat storage is one of the fluxes involved in the energy balance closure problem (Hendricks Franssena et al. 2010) and its knowledge is critical to evaluate the impact of the climatic changes on soil and vegetation temperature. Heat transfer in the soil compartment, can be measured using soil heat flux plates (Mayocchi and Bristow 1995). Moreover, in forests, heat storage in tree stems and canopies can be important. Its quantification can be realized using thermocouples inserted at different depths in stems, at different heights (bottom and top of trunks, main and secondary branches), on different azimuths (north and south for variation in sun exposition) and in trees among different status (dominant, codominant, suppressed). In addition to this relatively heavy experimental design, another crucial point is the determination of the wood-specific heat. This can become complicated because wood-specific heat is species-dependent and it may vary significantly during the day due to wood water changes (Čermák et al. 2007).

11.4 Impact of Ecosystem Management and Manipulation

In managed forests, stand structure is modified by thinning and clear-cuts. A good cooperation with the forest manager is necessary to collect quantitative information about the woody biomass exported and the part left on the ground. This information is essential to establish the complete carbon ecosystem balance. Unfortunately, in forests, this information is sometimes difficult to get, as several owners could share the surface representing the footprint area, with different ways to select the harvested trees and to operate the thinning. Management creates new heterogeneities (LAI, biomasses) in the footprint area which makes a regular map update necessary. The quite large surface of EC system footprint area in forests makes difficult any ecosystem manipulation (fertilization, water exclusion or addition, root exclusion, etc.), as it should be performed on the whole footprint area to analyze its impact in an unambiguous way on EC data.

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