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Application of the eddy-covariance method under the canopy at a boreal forest site in central Sweden

Vlad Pirvulescu

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Department of
Physical Geography and Ecosystem Science
Lund University
Sölvegatan 12
S-223 62 Lund
Sweden

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Department of Physical Geography and Ecosystem Science, Lund University

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Supervisors:

Meelis Mölder and Patrik Vestin

Department of Physical Geography and Ecosystem Science

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Abstract

The eddy-covariance (EC) method was applied at 1.5 m height, for the period 2007-2010 at Norunda, central Sweden, for calculating energy (sensible and latent heat) and carbon dioxide (CO_2) fluxes. The aim of this study was to assess the applicability of EC method above the forest floor. In 2007 an open-path EC system was used and in 2008, 2009 and 2010 a closed-path system was used. The energy and CO_2 fluxes showed a clear annual pattern, with maximum values occurring in the summer season or at the beginning of September. The values of the sensible heat (H) flux were low, below 10 Wm^{-2}, while the latent heat (LE) flux had annual daily average maximum values of 48 Wm^{-2} (2007), 18 Wm^{-2} (2008) and 27 Wm^{-2} (2009 and 2010). The mean annual CO_2 flux values were 2.5 µmol $m^{-2}s^{-1}$ (2007 and 2008), 3 µmol $m^{-2}s^{-1}$ in 2009 and 2.8 µmol $m^{-2}s^{-1}$ in 2010. The fluxes measured in 2009 and 2010 were on average higher than the ones measured in 2008, a possible consequence of the forest thinning operation, which allowed more net radiation to reach the ground and caused an increase in turbulence above the forest floor. LE and CO_2 fluxes measured with the open-path system had the biggest values and the largest variability under the entire study periods. The summer daily patterns of the energy fluxes showed higher LE than H throughout the entire 24 hours cycle. Daily summertime H flux was positive during 2009 and 2010, however a decrease was observed during afternoon, when the flux became negative. CO_2 flux was very variable in time in 2007 and during nights, a consequence of both the use of an open-path system and the data selection turbulence criterion, linked to the standard deviation of the vertical wind velocity. A mid-day minimum was observed for the summer CO_2 flux in 2009 and 2010, caused by photosynthesis inside the footprint area of the EC system. A comparison of EC and soil chamber data showed that CO_2 fluxes measured by both methods followed in general the same patterns; however there was a discrepancy between the recorded values. On average, the EC fluxes accounted for 39 to 52% of the soil chamber fluxes. These results are consistent to other studies. In order to have a complete understanding of the applicability of the EC method above the forest floor at Norunda, further studies are necessary in order to analyze the energy balance closure, the spectral corrections for the raw EC data and the treatment of CO_2 flux under very low turbulent conditions.

Key words: Eddy-covariance; Sensible heat flux; Latent heat flux; Carbon dioxide flux; Soil chambers; Open-path system; Closed-path system; Norunda.

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1. Introduction

The atmospheric boundary layer, or the planetary boundary layer, is the lowest part of the troposphere. In this layer the frictional stress decreases with height and the layer is influenced by the ground's thermal properties (Foken, 2008). The lowest 10% of this layer represent the atmospheric surface layer (ASL) and it is characterized by the fact that here the fluxes are relatively constant with height; therefore it is also called the constant flux layer (Foken, 2008). The height of the ASL is approximately 20-50 m from the ground in case of unstable stratification, and a few meters for stable stratification (Foken, 2008).

Turbulence is the main transport mechanism in the ASL and almost all the energy and gas exchange processes between biosphere and atmosphere are turbulent. The ASL is split also into two parts: the inertial and the roughness sublayers. The roughness sublayer is the part very close to the ground, where the ground elements are inducing shear stress to the flow. In the roughness sublayer the mean flow is 3-dimensional because it is mechanically and thermally influenced by the canopy elements (Raupach and Thom, 1981). In the inertial sublayer and over homogeneous surfaces similarity theories (e.g. Monin-Obukhov's) can be applied for estimating wind and momentum profiles. However, in the roughness sublayer the unmodified application of these theories is not valid.

Eddy-covariance (EC) is one of the most important methods to measure fluxes between biosphere and atmosphere in the surface layer. The method is complex and involves effort in the setup and for the data processing, but it is a direct and reliable way to measure fluxes of momentum, heat, water, CO_2, methane and other trace gases (Burba and Anderson, 2010). The development of the micrometeorological methods (especially EC method) for measuring biosphere-atmosphere gas exchange went on during the 1980s (e.g., Baldocchi et al., 1988). Presently, the global network of micrometeorological tower sites (FLUXNET) is using EC method to quantify exchanges of CO_2, water vapor and energy (Lee et al., 2004).

Most of the EC measurements are performed above the vegetation canopy, inside the roughness sublayer. The implementation of EC method under the canopy layer (above the forest floor) was also started during the 1980s (Baldocchi et al., 1986). Since then more studies have been performed in this field, especially about analyzing CO_2 exchange between forest floor and atmosphere (Baldocchi and Meyers, 1991; Baldocchi and Vogel, 1996; Law et al., 1999a), but also energy fluxes (Baldocchi et al., 2000). These studies have shown that the use of EC method under the forest canopy can be efficient in assessing the CO_2 and energy fluxes and that the method gives more insights about these surface exchange processes. Moreover, these processes are different above the forest canopy than underneath it. A comparison of under- and above-canopy EC measurements might show the strength and the location of the carbon sources and sinks, and different patterns of the energy fluxes as well.

As an example, measurements of CO_2 exchange with the EC technique may indicate an uptake above the canopy and a release just above the forest floor. Net radiation, latent (LE) and sensible (H) heat fluxes also have different values under and above the canopy. As a consequence of these differences, studying the CO_2 and energy fluxes above the forests floor is very important in understanding carbon and radiation balances in forest ecosystems. The application of EC above the forest floor is important because it is one of the most reliable methods to provide information about processes that occur at this level of the ecosystem. This perspective can be enlarged if EC data are compared to data resulting from other measurement method, e.g. soil chambers that measure soil CO_2 flux. The heterogeneity of the forest stands and the intermittence of the under-canopy turbulence are some of the limiting factors in the applicability of EC method above a forest floor (Baldocchi et al., 2000).

This project assesses the applicability of EC method for measuring CO_2 and turbulent energy fluxes (H and LE) under a mixed pine-spruce forest canopy, at Norunda site, central Sweden. The CO_2 flux measured with EC was compared with CO_2 flux measured with automatic soil chambers; the daily and annual variability of CO_2, H and LE fluxes was also studied in detail. The height of the EC measurements was 1.5 m above the forest floor and the time frame of the dataset ranged from 2007 to 2010, with summertime data mostly.

The **research objective** of this project is: *to increase the knowledge about the applicability of eddy-covariance method above a forest floor by assessing the measured CO_2, sensible heat and latent heat fluxes and by comparing eddy-covariance data with chamber data, from 2007 to 2010, at Norunda site, central Sweden*.

The **research questions** for this project are:

a. What are the absolute values and the time evolution of the under-canopy CO_2 flux measured by EC method at Norunda site?

b. What are the absolute values and the time evolution of the under-canopy sensible and latent heat fluxes measured by EC method at Norunda site?

c. Are there any differences between under-canopy eddy-covariance CO_2 flux and the soil chamber CO_2 flux and if so, how can these differences be explained?

d. What is the inter-annual variability of measured CO_2 and energy fluxes and how can this variability be explained?

Among the challenges related to this project, that can be mentioned, are: no established methodology for the use of EC method under a forest canopy; big amount of data to process (4 years); uncertainties related to the corrections to be applied to the raw EC measured data; different instrumentations used (open- and closed-path gas analyzers); uncertainties related to data selection criteria.

2. Background

2.1 Biosphere-atmosphere CO_2 and energy fluxes

CO_2 flux measured by the EC method represents the net amount between the respiration of both soil and vegetation and the plants photosynthesis. This difference is the net ecosystem exchange (NEE) and it has a big variability in time and space, being influenced by factors like temperature, soil moisture, plant nutrient availability, the disturbance regime of the ecosystem (Law et al., 1999a). Soil CO_2 flux can have a large contribution to NEE (Law et al., 1999a).

Soil respiration is the sum of the root autotrophic respiration (from plants) and of the heterotrophic respiration. Soil respiration rates are positively correlated with temperatures, precipitation and with the ecosystem mean net primary productivity (NPP, plant photosynthesis less plant respiration) of world's different biomes, with soil respiration exceeding the mean annual NPP on average by 24% (Raich and Schlesinger, 1992). Schlesinger (1977) estimated that in forests soil respiration averages to about twice the total annual detritus input of carbon from both above- and below-ground sources. Law et al. (1999b) estimated from chamber measurements that in a ponderosa pine forest the annual soil CO_2 flux was accounting for 76% of the annual ecosystem respiration. The sign convention for the CO_2 flux is that it is positive if there are CO_2 emissions to the atmosphere (atmospheric gain) and negative if CO_2 is taken up by the biosphere (atmospheric loss of CO_2).

Regarding the biosphere-atmosphere energy fluxes, the basic equation is represented by the energy balance at the Earth's surface:

$$R_n = H + LE + G + S, \qquad (1)$$

Where R_n is the net radiation, H is the sensible heat flux, LE is the latent heat flux, G is the ground heat flux and S is the storage component. In general, the storage component is low and often its value is not included in the energy balance equation. The sign convention for the energy fluxes is that R_n is positive if it is directed towards the surface and negative if it is directed away from the ground surface; the other fluxes are positive if they are directed away from the surface and negative if they are towards the surface.

2.2 Eddy-covariance method

EC is a direct method of measuring fluxes without need of any empirical constants (Foken 2008 and references therein). The air flow is regarded as being composed of a big number of eddies, each having 3-D components (horizontal and vertical). If one can measure in one particular spot the number or the energy content of the molecules that are moving upwards and downwards at a certain time, the flux can be calculated. The essence of this method is that the vertical flux can be calculated as a covariance of the vertical wind velocity and concentration of the entity being measured (Burba and Anderson, 2010). The turbulent flux density of a scalar (F) is proportional to the covariance between the vertical wind velocity (w) and the scalar concentration (c), F = $\rho_a \overline{w'c'}$, where ρ_a is the air density, the primes represent fluctuations from the mean (Baldocchi and Meyers, 1991), and the overbar is time averaging. The particular formulas for the fluxes are:

$$H = \rho_a c_p \overline{w'T'} \qquad (2)$$

$$LE = L\overline{w'\rho'_v} \qquad (3)$$

$$F_c = \overline{w'\rho'_c}\,, \qquad (4)$$

where F_c is the gas flux (CO_2, CH_4, etc.), ρ_a is the air density, c_p the specific heat at constant pressure (in J $kg^{-1}K^{-1}$), T the air temperature, L the latent heat of vaporization for water (in J kg^{-1}), ρ_v the water vapor density and ρ_c the gas density (in kg m^{-3}, µmol m^{-3} or equivalent units). H and LE are measured in Wm^{-2}, while F_c can be measured either in g $m^{-2}s^{-1}$ or in µmol $m^{-2}s^{-1}$ (or equivalent units).

Flux calculation by EC is based on the Navier-Stokes equations and on the Reynolds' postulates (Foken and Wichura, 1996). However, the relatively easy and straightforward algorithm that serves as basis for this method is also relying on a number of simplifications and assumptions. Among those, the most limiting ones are steady state conditions and horizontal homogeneity (Foken, 2008). The stationarity concept is related to the steady state conditions and it means that the statistics do not vary in time, while homogeneity means that the statistics do not vary in space (Foken and Wichura, 1996). According to Burba and Anderson (2010) the major assumptions used in EC include: measurements in a point represent an upwind area; measurements are done inside the boundary layer of interest; fluxes are measured only on the area of interest (the footprint is correctly chosen); the flux is fully turbulent; the terrain is horizontal and uniform; the instruments are detecting very small changes at very high frequency.

An important concept related to EC method is the footprint. The footprint represents the area around the measurement point from which the measured values come from. The measurements do not represent the area just below the sensor, but an area upwind from the measurement point (Foken, 2008 and references therein).

The typical EC instrumentation consists of a 3-dimensional sonic anemometer and a gas analyzer (open-path or closed-path). In the case of a closed-path gas analyzer there is an inlet sample tube for the air close to the anemometer. The open-path analyzer is also positioned near the anemometer, but in such a way that avoids wind distortion. However, the distance between the instruments should be chosen to be as small as possible. It is necessary that the instruments record data at high frequency (generally 10 or 20 Hz).

When applying the EC method, different results can be obtained when using different instrumentation setups, especially open- or closed-path gas analyzers (Massman and Lee, 2002). The time lag between vertical wind (measured by sonic anemometer) and gas concentrations (measured by gas analyzer) needs to be considered, since otherwise the two data series will not be correlated. In the case of the open-path gas analyzer the time lag is related to the distance between the anemometer and the analyzer. For the closed-path analyzers the time lag is linked not only to the physical distance between the anemometer and the inlet sample tube, but mostly to the tube length, which in some cases can be quite large. Time delay between sensors can be determined by cross-correlation analysis for each averaging interval and this method will find the maximum value of covariance between the two data series (Mauder and Foken, 2011). Another effect of the different instrumentation is that the closed-path gas analyzers attenuate temperature, CO_2 and H_2O density fluctuation inside the intake tube (Massman, 2004). There are also interactions between the gases and the walls of the inlet tube. As a result of the different behavior of CO_2 and water vapor in closed-path EC systems, lag times for water vapor are larger than those for CO_2 (Ibrom et al., 2007a).

The first steps in EC data processing and analysis are unit conversion and spike removal from the recorded raw data. Those two steps and also the further corrections can be included in the same software package as that used for processing EC data (e.g. EddyPro from Li-COR Inc.). Raw data will have spikes due to both electronic and physical noise and the removal of those spikes needs to be done with caution in order to avoid removing too much data (Burba and Anderson, 2010). A criterion for the spike removal can be defined as the data values that exceed the interval of the mean measured variable by a specified multiple of the standard deviation of that variable.

Data coming from the EC instruments are processed in order to remove trends and to calculate fluctuations and means (Moncrieff et al., 2004). The long-term data series are partitioned into equal time intervals for which, subsequently, fluxes are calculated. Choosing the time constant for which the fluxes are computed is an important operation in the data analysis process workflow. A short averaging time can lead to an omission of the effects of low frequency contribution to the fluxes, while for a very long averaging time the steady-state condition might not be fulfilled (Foken, 2008). It is commonly accepted in practice that time periods of between 10 and 60 minutes are appropriate to be used for calculating fluxes (Moncrieff et al., 2004). In most micrometeorological experiments, time averaging intervals of 15-30 minutes are commonly chosen, but at some sites a longer time interval can improve the measured EC flux and contribute to a better energy balance closure (Finnigan et al., 2003). There are several ways to decide on averaging time, such as to set a commonly used unit (e.g. 30 minutes or 1 hour) or to choose more time intervals, out of which the one with the largest flux should be finally considered (Burba and Anderson, 2010). Another method is to use an ogive test, which calculates the cumulative integral of the turbulent flux co-spectrum starting from the highest frequencies; when a constant value is reached at lower frequencies, the appropriate time interval has been found (Foken, 2008).

Detrending of EC raw data is the procedure used for calculating the fluctuations around the mean, for each averaging time interval. The mean values are subtracted from the measured values in order to calculate covariances. There are 3 ways to do this: block averaging (the mean removal), linear de-trending (linear trend removal) and the recursive filtering. Block averaging is the most common and simple method to use; however, complex terrains and rapid changes in concentrations in some regions may require the use of the other two detrending methods (Burba and Anderson, 2010).

EC raw data cannot be used directly for flux computation. A few corrections must be applied in order to reduce as much as possible the influence of some perturbing factors on the measured values. These corrections are needed because the ideal conditions for EC are very rarely found in nature; in the same time the instrumentation design, even if much improved during the last decades, still needs adjustments and careful interpretation of the results. A summary of the most important corrections is presented in Table 1.

Table 1: Summary of the most important corrections for the raw EC data.

No.	Correction	Correction determined by	Correction result
1	Coordinate rotation	Imperfect leveling of the sonic anemometer	Mean vertical wind (w) is set to 0
2	Spectral corrections	Loss of fluxes at different frequencies (eddy sizes)	Increase in flux values
3	Density correction (WPL)	Density variation because of fluctuations of temperature and water vapor	Exclusion of the effects of temperature and water vapor
4	Advection correction	Heterogeneous terrain	Inclusion of the effects of advection

A basic assumption of EC measurements is that the mean vertical wind is negligible, otherwise the vertical advective flux must be corrected (Foken, 2008). The coordinate rotation correction is caused by the fact that the sonic anemometer is never leveled perfectly and therefore w is not 0. An optimum leveling means that the vertical wind component should be perpendicular to the mean flow streamlines. If the anemometer is tilted, the other two wind components (u and v) are contaminating the vertical wind. There are three methods of coordinate rotation: the 2D and 3D rotation, which are also called the double and triple rotation methods, and the planar fit method (Finnigan, 2004). The double rotation is done in several stages and its purpose is to set mean w to 0. The planar fit method (based on Wilczak et al., 2001) is a more complex method. For this method, long-term u, v and w measurements can be used for a mathematical determination of a plane on which the true vertical flux should be perpendicular; the method is particularly helpful when measurements are taken on complex terrain (Burba and Anderson, 2010).

EC systems will always miss some fluxes, in the high or in the low frequency ranges. In order to compensate the losses at different frequencies or eddy sizes the spectral corrections are necessary. As a consequence of spectral losses all EC systems tend to underestimate the true atmospheric fluxes (Massman and Clement, 2004). The loss in the high frequency range is mainly caused by the spatial separation of sensors, pathlength averaging and dynamic frequency response characteristics of sensor signals (Mauder and Foken, 2006). Generally, the physical limitations of the instruments and any electronic filters limit the sampling of the smallest eddies, while the mean removal and the flux averaging methods limit the sampling of largest eddies (Massman and Clement, 2004). However, increasing the time interval for which the fluxes are calculated might determine an “extra” flux that is not related to the turbulent exchange, but more to longer-scale atmospheric events. For the spectral correction in the high frequency range, transfer functions have been developed (e.g. Moore, 1986, Moncrieff et al., 1997). In order to apply the transfer function method for the spectral correction, a model of the co-spectra is needed. Unlike the transfer function approach, in situ methods do not require such a model; their fundamental assumption is the co-spectral similarity between scalar fluxes (Massman and Clement, 2004). Co-spectra is a distribution of the covariance of w and a scalar by frequency (Burba and Anderson, 2010).

EC raw data need a density correction (also called WPL – from Webb, Pearman and Leuning), which is caused by the variation of the constituent’s density due to the presence of heat and water vapor fluxes (Webb et al., 1980). The WPL correction compensates for the effects of fluctuations of temperature and water vapor on measured fluctuations in CO_2, H_2O and other gases (Burba and Anderson, 2010). The application of the WPL correction to EC measured data is also influenced by the type of EC instruments, e.g. open-path versus closed-path gas analyzer (Massman, 2004). For closed-path EC systems, the WPL correction needs also to account for that water and CO_2 have different lag times inside the tube (Ibrom et al., 2007a).

In the case of heterogeneous terrain, the advection terms cannot be neglected (Foken, 2008). As a consequence, an advection correction is necessary. Lee (1998) showed that the ecosystem's NEE consists of 3 components: the storage below the point of measurement, the eddy flux and a mass flow component arising from the horizontal flow convergence/ divergence or a non-zero mean vertical velocity. The last term becomes very important over tall vegetation and when the vertical gradient of the atmospheric constituent is large, e.g. CO_2 in forests at night (Lee, 1998).

All these above-mentioned corrections are very important to consider in the EC flux calculation process. Combined, they may sum to over 100% of the initial flux value, especially for small fluxes or for yearly integrations (Burba and Anderson, 2010), showing the necessity for a careful and accurate application of the corrections.

Data quality control is another important step in EC data processing. The data quality has the purpose to check if the EC basic assumptions are fulfilled. This process is based on the steady state test and on the integral turbulence characteristics tests (Mauder and Foken, 2004). As a consequence of these tests, a flagging system is created for each test, and then all the results are merged into an overall quality flag system.

A way of verifying the accuracy of EC method for flux measurement is the check of the energy balance closure. Equation (1) may be divided in two parts: the available energy (AE = Rn-G-S) on one side and H+LE fluxes on the other side. Since H and LE can be calculated with EC, and AE can be measured with other instruments (radiometers, soil heat plates, etc.), the equality between H+LE and AE indicates good results of the EC method. However, in practice, a perfect closure of the energy balance equation is not encountered. Wilson et al. (2002) performed a study at 22 FLUXNET sites regarding energy balance closure. They showed that there was a mean imbalance in the equation of about 20%, with either an underestimation of H+LE or an overestimation of the AE. The same authors concluded that there is no perfect closure of the energy balance for sites using either open- or closed-path gas analyzers and also for sites located either on flat or on sloping terrain (Wilson et al., 2002). Moderow et al. (2009) argued that the uncertainty in the AE alone cannot explain the bad closure of the energy balance. The energy imbalance is also determined by the uncertainties in the EC flux corrections, and because the H+LE term is measured by EC there is a suspicion that the CO_2 flux measured by the same method might be also underestimated (Massman and Lee, 2002).

EC applicability for calculating nighttime fluxes has also some drawbacks. During these periods the CO_2 flux may be underestimated because nighttime turbulence is generally low. H and LE fluxes are generally very low during nights and therefore their value is not too much influenced by the lack of turbulence. The most important and widely-accepted reason for the nighttime CO_2 flux underestimation is the presence of landscape scale movements associated with drainage flow or land breezes that take place under low turbulence, and under these conditions advection becomes a very important term that cannot be neglected (Papale et al., 2006). As a consequence of the drainage flow, close to the ground and under the measurements point, EC instruments don't capture the CO_2 flux. A way to resolve this problem is to define a u_* (friction velocity) threshold value, as a proxy for turbulence intensity, and to use only the flux values for which the friction velocity is above the threshold; also to replace the remaining values with fluxes derived from turbulent nights according to their response to climate (Feigenwinter et al., 2010, and references therein). However the value of this u_* threshold is very site specific (Massman and Lee, 2002). Even if this method is convenient and straightforward it is also bringing big uncertainties and needs to be applied with care (Papale et al., 2006).

2.3 Canopy and below-canopy turbulent exchange processes

Turbulence inside the canopy layer has been the subject of many studies during the last decades (e.g. Raupach and Thom 1981, Baldocchi and Meyers 1988, Lee and Black 1993, Finnigan 2000). Among the most important features that describe turbulence inside the canopy layer, that can be mentioned, are: the canopy acts as a decoupling layer between the atmospheric layers above and below it (Foken, 2008); organized structures in the overlying boundary layer determine the nature of canopy turbulence (Raupach and Thom, 1981); turbulence is intermittent and the flow is highly turbulent (Baldocchi and Meyers, 1988); the momentum transfer within and just above the canopy is mostly determined by penetration of fast, downward moving gusts (Finnigan, 2000); the diffusion models are not applicable in the canopy environment (Raupach and Thom, 1981); in open canopies, where there is substantial net radiative exchange at ground surface, local buoyancy becomes a very important process that generates turbulence (Lee and Mahrt, 2005); the thermal effect (buoyancy) is very important in dictating the magnitude of gusts inside tall vegetation (Leclerc et al., 1991); there is a high intensity of turbulence in the canopy crown and close to the ground level, but smaller in the trunk space, where the production of turbulence is weak (Launiainen et al., 2007); below-canopy fluxes are intermittent and the sampling error is large (Law et al., 1999a). In the same time, a decrease in measurement height increases the high frequency content in the fluxes and decreases the low frequency content (Massman and Clement, 2004). All these characteristics combined determine a different pattern of turbulence (and therefore also of EC method) below the forest canopy (in the trunk space and just above the forest floor) than above the canopy, where most part of the EC measurements are performed nowadays.

The daily cycle of temperature in a forest is dominated by processes like increased heating of the canopy during daytime (while the understory layer and the soil temperatures are lower) and higher canopy cooling during nights (while the understory temperatures remain higher). As a consequence, in the particular case of forests, temperatures are increasing with height during daytime, there is a stable stratification; and vice versa an unstable stratification during nighttime (as the temperature profile decreases with height) (Foken, 2008). The wind speed is also dampened inside the forests; however, because of the decreased shear in the trunk space a secondary maximum in wind profile occurs at these heights (Shaw, 1977).

The study published by Denmead and Bradley (1985) showed that inside a forest the fluxes can deviate from the general law and be opposite to their corresponding gradients. Therefore this phenomenon is named counter-gradient flux and it is determined by the short-term turbulent movements inside the canopy (Denmead and Bradley, 1985). As a consequence, the gradient method, based on eddy diffusivity coefficients, is not useful for calculating the turbulent fluxes inside or underneath the canopies (Finnigan, 2000 and references therein). Therefore, fluxes need to be calculated by using direct methods, such as EC (Launiainen et al., 2005).

2.4 CO_2 flux from chamber measurements

Chamber measurements have been used for measuring soil emissions of CO_2 and other trace gases for many decades. This method is the most direct way of measuring soil and litter respiration (Davidson et al., 2002). However, the method implies also difficulties. Soil carbon flux is difficult to measure because of the soil heterogeneity and ground vegetation increase this heterogeneity (Lankreijer et al., 2009). The chamber measurements are made on a very small area and there is need for a big amount of data in order to scale up the measurements to the ecosystem level (Lavigne et al., 1997). As a consequence of the high soil heterogeneity, the measurements from chambers have a very high spatial variability. Therefore, the chambers can provide information about the spatial distribution of the gas exchange processes, while EC measurements indicate more an average for the measurement area (Launiainen et al., 2005).

Soil CO_2 flux heterogeneity is a limiting factor when comparing fluxes measured with chamber method and EC fluxes. However, the combination of these two methods has some benefits since chamber data provide a better spatial resolution while EC a better temporal resolution (Law et al., 1999a). Another benefit is that chambers might give more insight about different sources of below-canopy fluxes, while EC can identify processes neglected by chamber measurements, like understory photosynthesis (Law et al., 1999a).

3. Methodology

3.1 Site description

The Norunda site is located in central Sweden (60^{o}5'N, 17^{o}29'E, 45 m altitude), approximately 30 km north of the city of Uppsala. The station is a part of FLUXNET, a global network of micrometeorological flux measurement sites that measure the exchanges of carbon dioxide, water vapor and energy between the biosphere and the atmosphere (Baldocchi et al., 2001). The main ecosystem is represented by the boreal forest, a coniferous forest dominated here by Scots pine (65%, *Pinus sylvestris*) and Norway spruce (33%, *Picea abies*) with a small fraction of deciduous trees, and heights of 24-28 m (Feigenwinter et al., 2010). According to Lagergren et al. (2008) the leaf area index (LAI) is 4-5 (higher on the spruce plots) and the dominant height of the forest is 27.8 m. The forest is managed and it was regenerated from seeds left after harvest. There are patches of older forest (around 100 years) on one quarter of the area, middle-aged (50-100 years) on half of the area, and younger forest, under 50 years (Lindroth et al., 1998). The forest around the measurements area (both EC and chambers) was thinned in October 2008 (Patrik Vestin, personal communication). After the thinning the LAI went down to around 2.7, in 2009 and 2010 (Fredrik Lagergren, personal communication). The Norunda forest acts as an atmospheric source of CO_2 over a long period of time, as suggested by a study of Lindroth et al. (1998).

The mean annual temperature is 5.5^{o}C (1961-1990) and the mean annual precipitation 527 mm (Lundin et al., 1999). The climate is more maritime than on other boreal forest sites in the Fluxnet network (http://fluxnet.ornl.gov/site/730). The growing season normally lasts from mid-April to the second half of October (Lindroth et al., 1998).

The topography of the area is flat. The conditions make Norunda an almost ideal location for EC measurements. The soil is a sandy glacial till with moderate to high occurrence of boulders and it is covered with mosses and dwarf shrubs (Feigenwinter et al., 2010), out of which the most important species are blueberry (*Vaccinium myrtillus*) and lingonberry (*Vaccinium vitis-idaea*). According to Lundin et al. (1999) the soils from Norunda are podzolic and they have a thin layer of organic matter at the surface.

Photo 1: open-path EC system 1.5 m above the forest floor at Norunda (photo by Meelis Mölder)

Photo 2: soil chamber system at Norunda (photo by Patrik Vestin)

3.2 Eddy-covariance measurements

Long-term under-canopy EC measurements were performed between 2007 and 2010 at Norunda site. The EC setup for this study was mounted at approximately 70 m south-west from the main EC tower. In 2007 the measuring period was from June 5th to November 2nd, in 2008 from May 8th to October 24th, in 2009 from May 4th to November 5th and in 2010 from May 5th to November 2nd (Table 2). Inside these time intervals there were periods when the LE flux was not measured due to instrument mal-function (July 22nd – August 10th, 2008) or periods with no EC measurements (August 18th – August 26th, 2008, August 5th – August 14th, 2009). During 2007 the instrumentation setup was the following: a Metek USA-1 (Metek GmbH, Germany) ultrasonic anemometer and a LI-7500 (Li-Cor Inc., Lincoln, NE, USA) open-path gas analyzer (Photo 1 - setup A). In 2008, 2009 and 2010 the instruments used were: Metek USA-1 (Metek GmbH, Germany) ultrasonic anemometer and LI-7000 (Li-Cor Inc., Lincoln, NE, USA) closed-path gas analyzer (setup B). Data were recorded at 20 Hz frequency and the measuring height was 1.5 m. In setup A the open-path gas analyzer had 27 and 22 cm northward and vertical separation from the anemometer, respectively. In setup B the inlet for the closed-path gas analyzer was located 20 cm below the mid-part of the anemometer. The LI-7000 closed-path analyzer had an inlet tube of 16 m with an inner diameter of 4 mm and a nominal flow rate of 8 l/min. For all study periods, measured atmospheric pressure data were also used.

3.3 Chamber measurements

Soil CO_2 flux was measured with automatic chambers (0.105 m^3 volume) located approximately 50 m south-west from the under-canopy EC tower (Photo 2). There were continuous measurements during the following periods: May 10th, 2007 to June 9th, 2008; April 29th to July 14th, 2009; August 1st to November 30th, 2009; June 15th to December 31st, 2010 (Table 2). From July 2008 to April 2009 the system was moved to another location. The chamber system comprised of a total number of 6 chambers, mounted on steel collars and connected to a LI-820 (Li-Cor Inc., Lincoln, NE, USA) gas analyzer. Between August 1st and November 30th, 2009, only 3 chambers out of 6 were in use. All the chambers were transparent and the inside vegetation was left intact. Therefore not only the soil respiration was measured, but also plant photosynthesis. The CO_2 flux represents the sum of these two processes. The system setup allowed only one chamber to work at a time, while the other chambers were open. There was a 5 minute measurement cycle that consisted of the following successive steps: in the beginning of the cycle for the first 2 minutes air was mixed inside the chamber by a fan, with the chamber lid open; after this step the chamber lid was closed, the inside air continued to be ventilated and successive measurements of CO_2 concentration were taken. The air was circulating in the tubes at a mean flow rate of 10 l/min, while the sample flow through the gas analyzer was set to 0.8 l/min. At the end of the cycle there were measurements of photosynthetic active radiation (PAR), soil temperature and soil moisture for all the chambers. After that the chamber lid was opened and a new measuring cycle started for the next chamber. There were a total of 18 CO_2 concentration measurements per cycle, at 10 seconds time intervals. Chamber CO_2 flux was calculated by using linear regression of CO_2 concentrations versus time.

Table 2: Measurements periods for both EC and chamber fluxes. Red represents EC data and blue chamber data (one colored month represents more than 15 days of measurements in a month). The exact periods are presented in column 3.

Year	Measurements system	Measurements periods	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007	EC	Jun 5 - Nov 2												
	Chambers	May 10 - Dec 31												
2008	EC	May 8 - Oct 24												
	Chambers	Jan 1 - Jun 9												
2009	EC	May 4 - Nov 5												
	Chambers	Apr 29 - Jul 14; Aug 1 - Nov 30												
2010	EC	May 5 - Nov 2												
	Chambers	Jun 15 - Dec 31												

3.4 Flux calculations

EC fluxes were calculated using EddyPro 4.1 software package. The raw data consisted of 30 minutes ASCII files. The averaging interval was also chosen to be 30 minutes. The detrending method used was the block averaging and the double rotation method was selected for the coordinate rotation. Spikes in each raw data file were removed using a standard deviation criterion: 5 for the vertical wind speed and 7 for water and CO_2. In order to compensate the time lags between the sonic anemometer and the gas analyzer the method of maximum covariance was considered. Time lags were automatically calculated by Eddy Pro software, being different for open- and closed-path gas analyzers (for more details please see Eddy Pro 4.1, Li-Cor Inc., 2012 user guide).

Density fluctuations were compensated by choosing the WPL correction (Webb et al., 1980), different for open- and closed-path systems. Spectral corrections represent also a very important part because omitting these corrections the fluxes will be underestimated. The chosen algorithms applied for the EC fluxes calculation were Moncrieff et al. (1997) for corrections in the high frequency range and Moncrieff et al. (2004) for corrections in the low frequency range.

In this study the flux footprint for the EC measurements was not determined. Launiainen et al. (2005) calculated the footprint area inside a boreal pine forest trunk space, for EC measurements at 3 m above the forest floor. Their results showed that 80% of the flux originated from within 50 m from the measurement point. Law et al. (1999a) performed EC measurements at 2 m height in a very open canopy (ponderosa pine forest) and their calculated footprint ranged from 2 to 160 m, with 90% of the fluxes from within 40 m from the measurement system. The results of these studies show that the footprint area for EC measurements above the forest floor is not so large and this was considered valid also for the case of this project.

3.5 Data quality analysis and selection criteria

Flux quality flags were calculated for each 30 minute interval by using the scale ranging from 1 to 9, proposed by Foken (Foken et al., 2004 and references therein, Mauder and Foken, 2011). This flagging system is based on integral turbulence characteristics (calculated for w, u and T) test and on the steady-state test. Classes 1-3 can be used for fundamental research, 4-6 are available for general use, 7-8 are only for orientation and class 9 should always be excluded from the dataset (Mauder and Foken, 2011). For the EC dataset of this study only the 9-flag fluxes were excluded.

The LI-7500 open-path gas analyzer (used in 2007) provided an internal diagnostic value, for each 20 Hz measurement. The quality flag values ranged from 249 to 255, with 249 values being of good quality data (Meelis Mölder, personal communication). An average of the quality flag for each 30 minutes interval was calculated. The 30 minutes average quality flags were plotted together with water vapor concentrations measured from EC and from a profile in the main tower, at 8.5 m height (results not shown here). The 2007 dataset was split into 10 time periods. For each time period a baseline of the quality flags was considered to be meaningful and to be a proxy of good-quality measured data. By checking both the evolution of the quality flags and of the measured water vapor, data that were equal or lower to the baseline were selected for use. Only baselines of 249 and 250 were accepted, depending on the period analyzed. Data records with quality flags higher than the selected baselines were considered bad data and were removed from the dataset. The LI-7500 quality flag criterion was used in addition to the Foken quality-flag system to select EC data for 2007.

In addition to the spike removal from each raw data file, outliers can occur also between the resulted half hourly calculated fluxes. The selection criterion used for the outliers' removal was to exclude the values that were not inside the interval of mean +/- 3 standard deviations. This outlier removal criterion was applied for each analyzed flux (H, LE and CO_2). The spike removal lead to an exclusion of less than 5% of the data of each flux and for each analyzed year. However, in 2008, 16% of the LE flux values were considered spikes and were excluded from the dataset.

Nighttime CO_2 fluxes might be underestimated because of low turbulence and insufficient mixing of air. As a solution to this inconvenience, a u_* correction can be performed, even if this method has some uncertainties involved (Papale et al., 2006). However, under a forest canopy turbulence is inactive in the sense that it is not associated with much momentum transport (Finnigan, 2000). Therefore the friction velocity (u_*) does not represent the turbulent mixing and its use should be avoided inside the canopy (Launiainen et al., 2005). These authors recommend using the standard deviation of the vertical wind velocity, as a proxy for under-canopy turbulence. In the present study the same approach was used, i.e. a threshold of standard deviation of vertical wind (σ_w), as turbulence criterion, below which measured CO_2 fluxes were very scattered (Figure 1). The value of this threshold was set to 0.07 ms^{-1} (as in Launiainen et al., 2005) and the fluxes measured when σ_w was below the threshold were disregarded. By setting a bigger threshold value, too many data would be excluded from the dataset. The turbulence criterion was applied only for CO_2 flux because during nighttime, when the turbulence criterion is mostly not fulfilled, H and LE fluxes are very low, almost 0 or slightly negative. The turbulence intensity criterion lead to an exclusion of 59 to 80% of nighttime CO_2 flux values, for each studied year.

The main selection criterion for the chamber CO_2 fluxes was the value of the coefficient of determination (r^2) for the regression line. However, if there is vegetation present inside the chamber, photosynthesizing during the daytime, the r^2 values can be much lower without necessarily meaning that the measured CO_2 flux is wrong. Photosynthetic activity inside the chamber can determine more scattered values of CO_2 concentrations. By applying a high r^2 criterion some correct CO_2 fluxes can be discarded and this will lead to a total flux overestimation, since in general the discarded fluxes will be lower because of plant photosynthesis. To overcome this situation, CO_2 flux and r^2 values were plotted for each chamber (results not shown here) to see if photosynthesis might be a cause of the low r^2. In this latter case, an r^2 threshold value of 0.4 was applied. Otherwise a 0.9 value for r^2 was used as data selection criterion. For most part of dataset the 0.9 threshold value was suitable for the data selection. The 0.4 threshold value was applied only for one chamber that was in use between May and July 2009. The other selection criteria used for the chamber fluxes were: CO_2 flux values between -5 and 20 µmol $m^{-2}s^{-1}$ were considered acceptable (to avoid outliers); cell pressure lower than 98 kPa and first CO_2 concentrations between 300 and 800 ppm were accepted. The data that did not satisfy all these criteria were not used in the analysis.

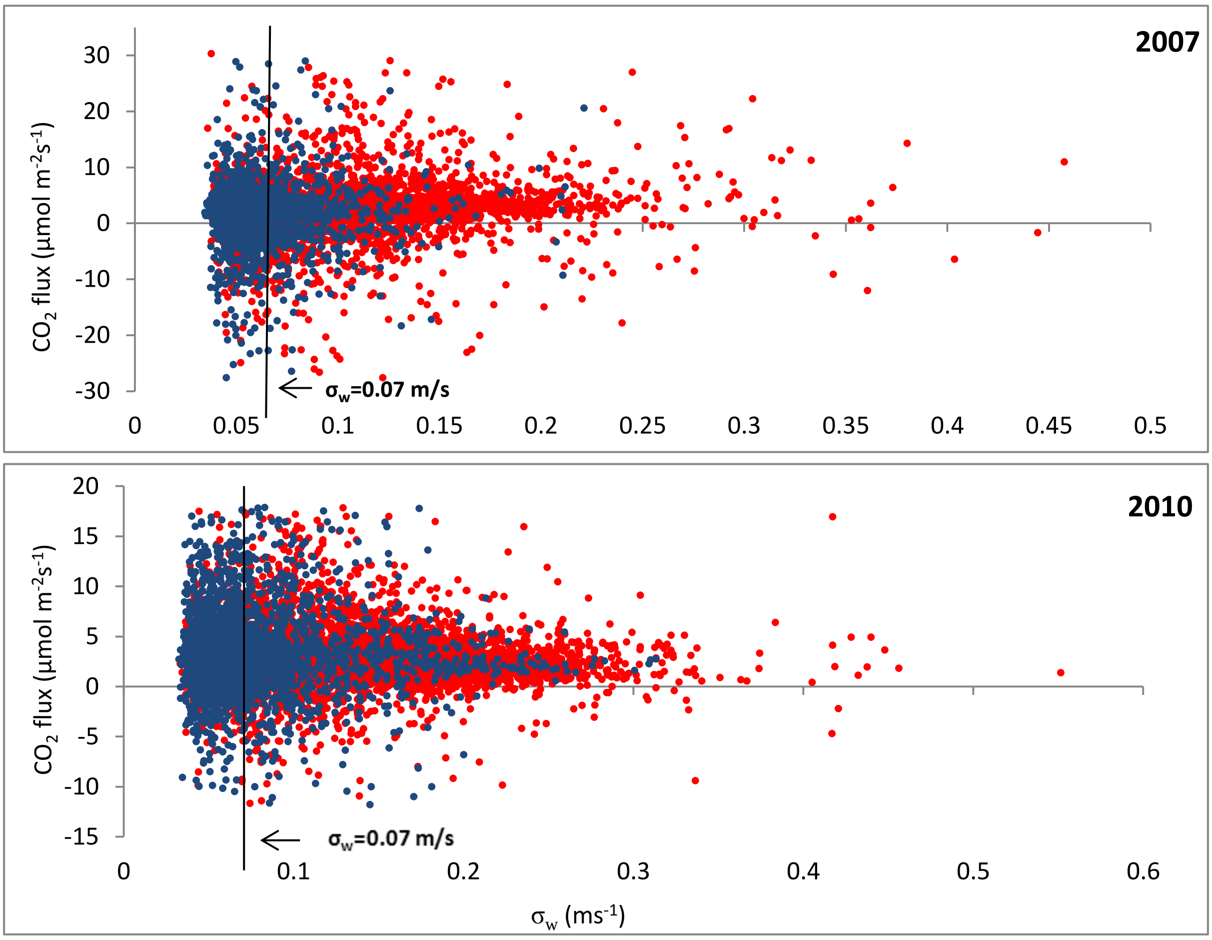


Figure 1: Under canopy EC CO_2 flux (half hourly values) as a function of the standard deviation of the vertical wind velocity (σ_w). The black vertical line represents the threshold value for the turbulence criterion. Red circles represent the daily fluxes and blue circles the nighttime fluxes. The other 2 years (2008 and 2009) show similar results.

4. Results

4.1 Spectral corrections

The spectral corrections in the high frequency range have an impact on the EC fluxes, especially above the forest floor where most part of the turbulence is represented by small-sized eddies. Spectral corrections can be performed on raw EC data by using either transfer functions or in-situ methods. A comparison between EC fluxes calculated without any spectral correction and an analytic method (that uses transfer functions) and an in-situ method (which is based on co-spectral similarity between scalar fluxes) was performed in this study for the 2008 summer dataset, when a closed-path system was used (Figure 2). The analytic method is described in the study of Moncrieff et al. (1997) and was used as spectral correction in the high frequency range for all the periods of this study. The in-situ method is described by Ibrom et al. (2007).

Both spectral correction methods showed higher fluxes compared to the case where no spectral correction was used. The Moncrieff et al. (1997) method gave LE and CO_2 fluxes higher by 13 and 8.5%, respectively, compared to uncorrected fluxes. The Ibrom et al. (2007) method, on the other hand, gave LE and CO_2 fluxes higher on average by 9 and 6% compared to uncorrected fluxes (Figure 2). LE and CO_2 fluxes calculated using Moncrieff et al. (1997) spectral correction were higher than the ones calculated using Ibrom et al. (2007b) method. The effects of the spectral corrections to the H flux were very small (results not presented here). The regression line coefficient of determination (r^2) had high values for all the analyzed cases. The fluxes calculated using different spectral corrections followed the same pattern during the 2008 summer, the lowest values being of the fluxes with no spectral corrections and the highest values of the fluxes calculated with Moncrieff et al. (1997) correction.

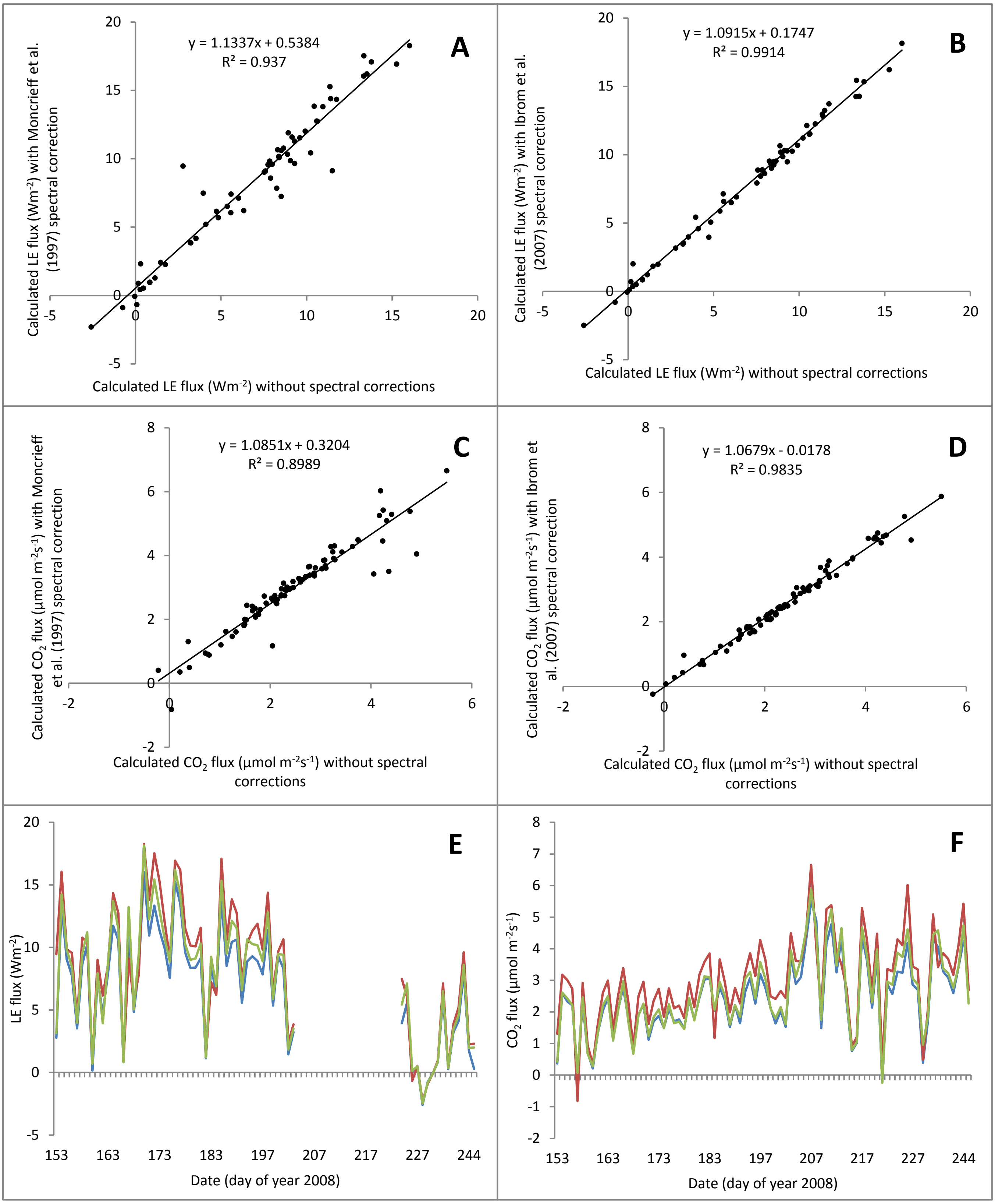


Figure 2: Spectral corrections comparison (daily averages). A: linear regression of LE flux calculated with Moncrieff et al. (1997) correction versus LE flux calculated without spectral corrections. B: linear regression of LE flux calculated with Ibrom et al. (2007) correction versus LE flux calculated without spectral corrections. C: linear regression of CO_2 flux calculated with Moncrieff et al. (1997) correction versus CO_2 flux calculated without spectral corrections. D: linear regression of CO_2 flux calculated with Ibrom et al. (2007) correction versus CO_2 flux calculated without spectral corrections. E: Time evolution of LE fluxes calculated without spectral corrections (blue line), with Ibrom et al. (2007) correction (green line) and with Moncrieff et al. (1997) correction (red line). F: Time evolution of CO_2 fluxes calculated without spectral corrections (blue line), with Ibrom et al. (2007) correction (green line) and with Moncrieff et al. (1997) correction (red line).

4.2 Annual patterns of H, LE and CO_2 fluxes

H and LE fluxes measured with EC at Norunda site showed a clear annual pattern throughout the entire study period (Figure 3). In this study, the term "annual" reffers just to the study period from one calendar year (e.g. for 2007 - June to November) and not to the entire year. The maximum values of the fluxes were in the summer season and a visible decline is observed during autumn, from September onwards. Under-canopy H flux showed very low values, almost all negative or close to 0 in all the analyzed years. However, in 2009 and 2010, after the forest thinning, the summer values of H became positive, even if still low (around 5 Wm^{-2} daily averages). The maximum values of daily average LE were also recorded during summer and they were around 48 Wm^{-2} (2007), 18 Wm^{-2} (2008) and 27 Wm^{-2} (in 2009 and 2010). Both H and LE values fell to almost 0 in October. Missing data are related either to periods where the LE was not measured due to instrument mal-function (e.g. July 22nd– August 10th, 2008) or to short periods with no EC measurements (e.g. August 18th – August 26th, 2008; August 5th – August 14th, 2009).

Under-canopy EC CO_2 flux at Norunda was positive throughout the studied period, which means that the forest floor was a net source of carbon to the atmosphere (Figure 4). The daily average values of CO_2 flux showed a maximum in the summer season. This maximum is very clear for 2009 and 2010, when the flux increased from spring until the highest values were reached in mid-August (2010) or beginning of September (2009). A similar pattern can also be seen in 2008, even if it is not so clear as in 2009 and 2010. The annual cycle of CO_2 flux in 2007 shows more scattered values during summer (even negative daily fluxes) and a clear decrease during autumn. These scattered values could be a result of the use of an open-path EC system in. The missing values are related to lack of EC measurements (same periods as for H and LE fluxes, August 2008 and August 2009).

During 2007, the CO_2 flux had a maximum value of approximately 10 µmol $m^{-2}s^{-1}$ and an average value of 2.5 µmol $m^{-2}s^{-1}$ (Figure 4). During this year negative daily average values can be encountered, especially in the summer period. In 2008 the maximum recorded value was 7.7 µmol $m^{-2}s^{-1}$ and the average was the same as in 2007, 2.5 µmol $m^{-2}s^{-1}$. In 2009 and 2010 the maximum values of the daily average CO_2 flux were around 7 µmol $m^{-2}s^{-1}$ and the average flux values were 3 and 2.8 µmol $m^{-2}s^{-1}$ respectively. Therefore the CO_2 flux was on average slightly higher in 2009 and 2010 comparing to 2007 and 2008. The summer peak of CO_2 flux is expected since the soil respiration is well correlated with soil temperatures, which are higher in the summer season.

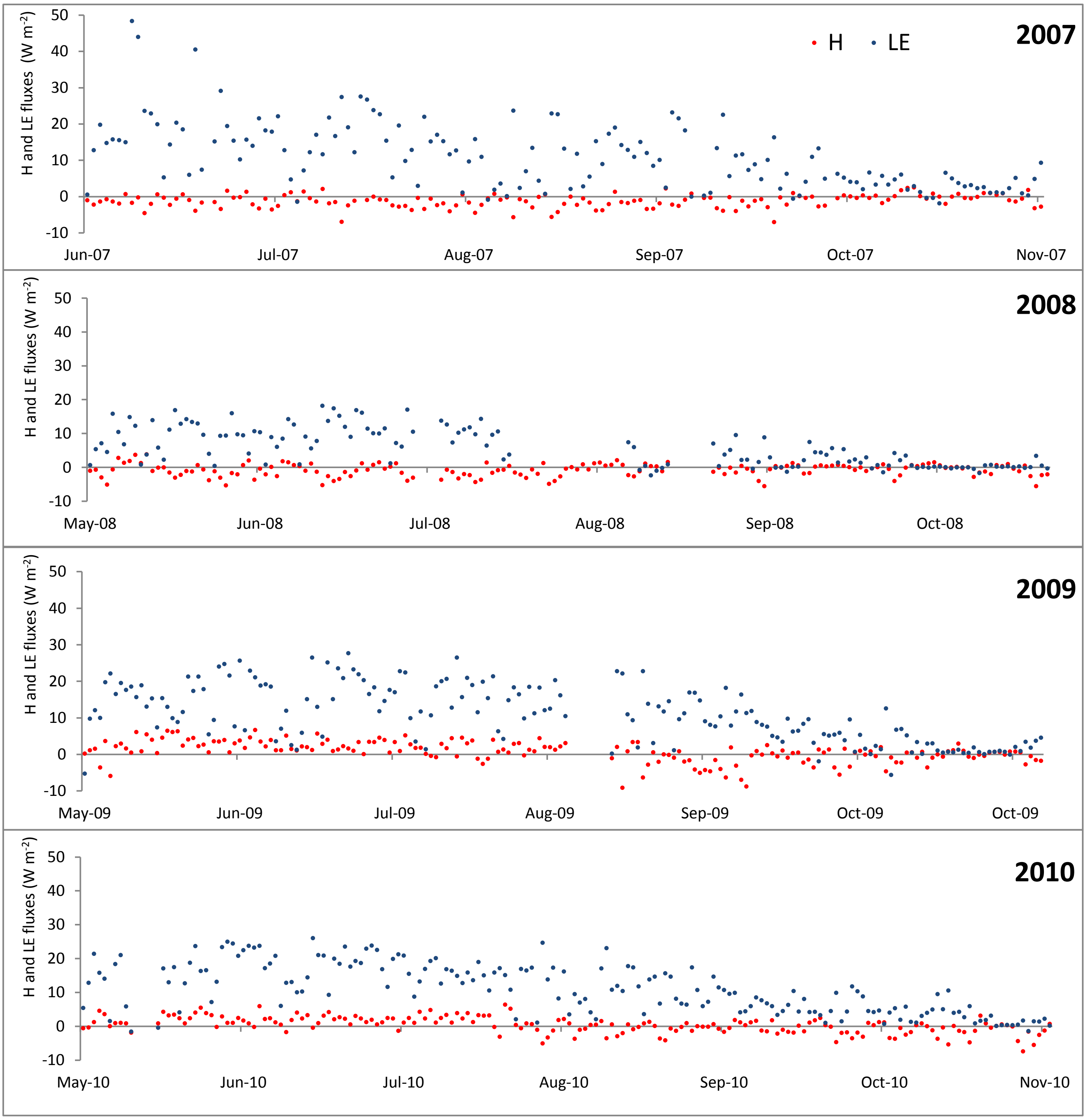


Figure 3: The annual patterns (daily averages) of under-canopy sensible (H) and latent heat (LE) fluxes measured with EC at 1.5 m height. Red circles represent H flux and blue circles LE flux. Missing data are due to instrument mal-function or to lack of measurements.

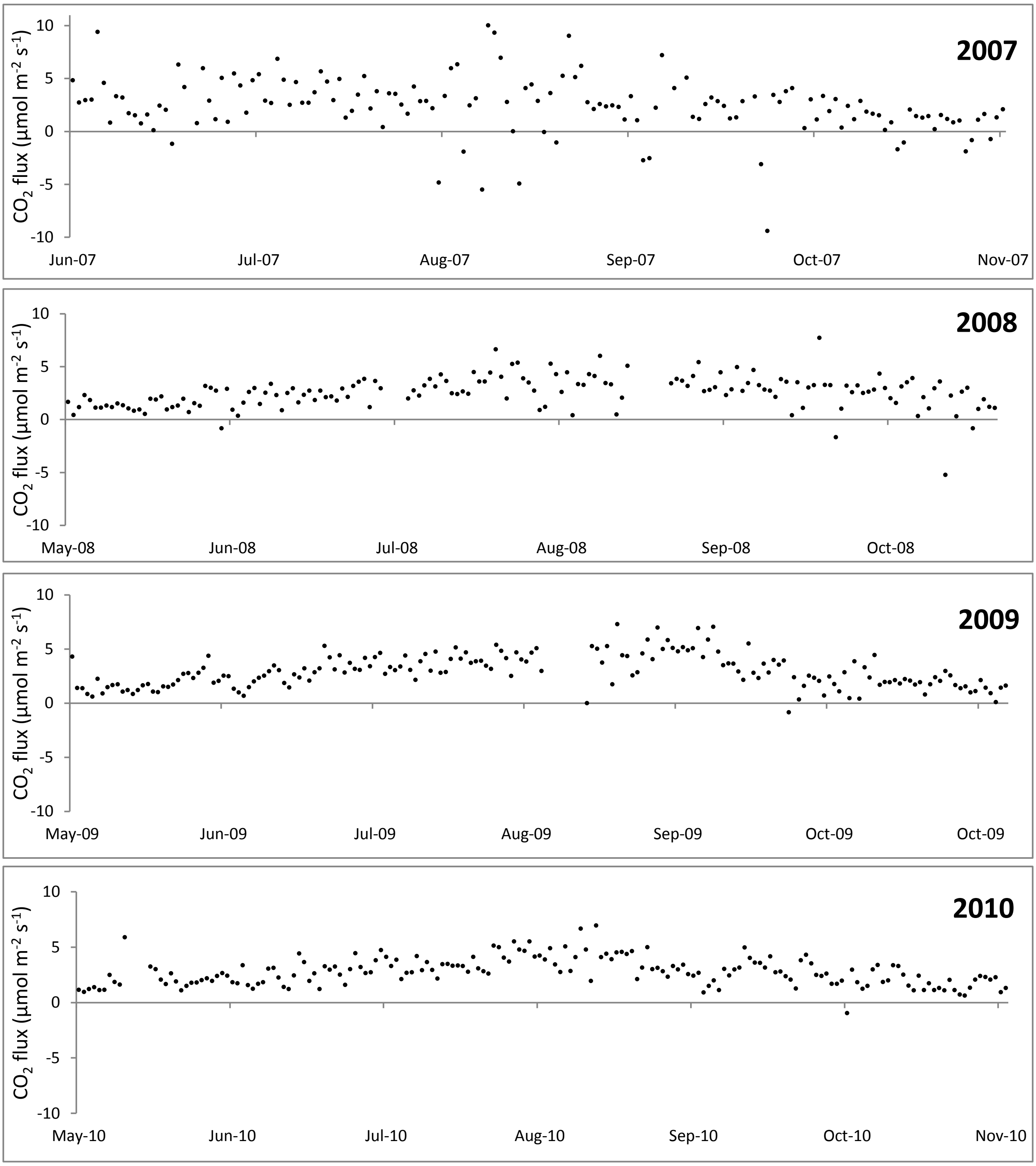


Figure 4: The annual patterns (daily averages) of CO_2 flux measured with EC at 1.5 m height. Missing values are caused by lack of measurements.

4.3 Summertime diurnal cycles of H, LE and CO_2 fluxes

The diurnal cycles of energy (H and LE) and CO_2 fluxes were analyzed in this study for the summer seasons of all the years (June to August). Summer season was chosen because it had the largest data coverage and the highest exchange rates.

The diurnal cycle of H and LE in 2007 and 2008 (Figure 5) showed low values for H throughout the 24 hours cycle. H was slightly negative during daytime in 2007 and 2008, with values ranging from -5 to about 0 Wm^{-2}. In 2009 and 2010 it can be seen that H became positive during daytime, with maximum values reaching approximately 10 Wm^{-2} (Figure 5). After reaching the maximum around noon, H became negative during the late afternoon. LE flux was almost 0 during nighttime (but slightly positive) and positive during daytime, with maximum values reaching 50 Wm^{-2} in 2007, 29 Wm^{-2} in 2008 and around 43 Wm^{-2} in both 2009 and 2010. LE reached also its maximum around noon (2008-2010) or a few hours later (in 2007). EC measured LE flux was highest in 2007 (when the open-path gas analyzer was used) and lowest in 2008. 2009 and 2010 had the same LE flux and an increase from 2008 can be noticed. The different behavior of both H and LE in 2009 and 2010 comparing to 2008 can be a result of the thinning treatment for the forest plot, which determined additional energy fluxes between the forest floor and the trunk space atmosphere. In the same time,

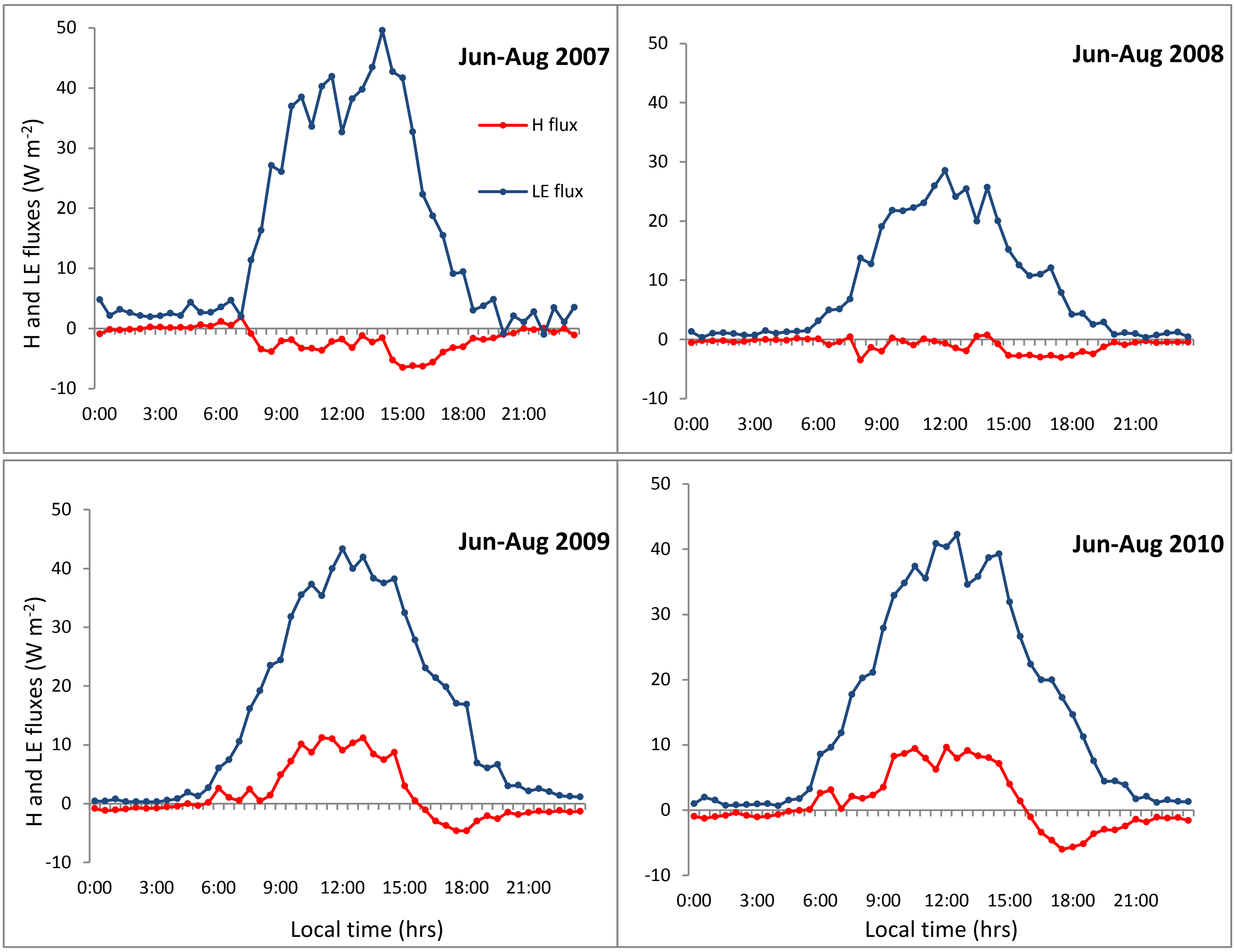


Figure 5: Diurnal cycle (half-hourly averages) of summer (June-August) under-canopy H and LE fluxes, measured with EC at 1.5 m height. Red line represents H and blue line LE.

higher LE measured in 2007 can be a result of the different instrument setup used (open-path system).

The evolution of H and LE fluxes was analyzed for 3 consecutive days in 2009 (July 12, 13 and 14). The diurnal pattern of the fluxes can be easily distinguished (Figure 6). LE and H were very low, close to 0, during nights. Both fluxes started to increase after the sunrise and they reached a maximum either before or around noon (for H) or around noon or a few hours later (for LE). H flux became negative in the afternoon. Both H and LE were variable in time in the sense that changes in the value of the fluxes occurred abruptly. However these changes did not significantly modify the daily pattern. These sudden changes in the fluxes values were probably determined by the intermittent nature of turbulence in the trunk space of the forest.

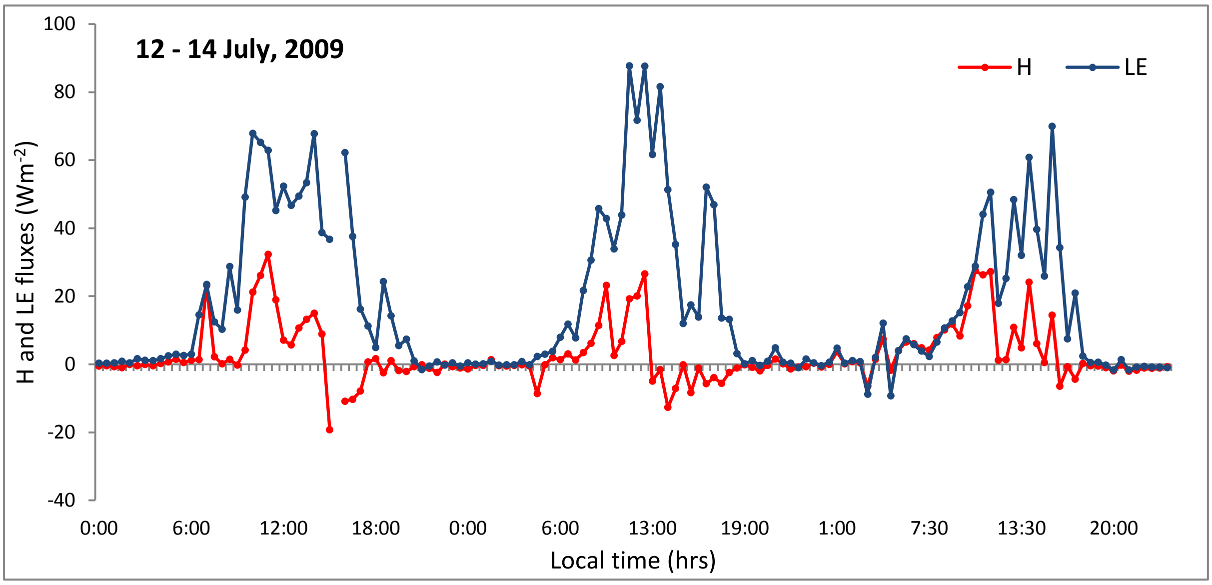


Figure 6: H and LE fluxes evolution during the period July 12th – July 14th, 2009. Red line represents H and blue line LE. Values represent half-hourly calculated EC fluxes.

The diurnal summer cycle of the CO_2 flux had different patterns in the 4 studied years (Figure 7). However, the flux was positive throughout the day, even though some sudden drops brought the measured values close to 0. There was similarity between the daily cycles in the summer of 2009 and the summer of 2010. In these cases the CO_2 flux showed a decrease during daytime which can be associated with the photosynthetic activity, enhanced also after the thinning operation. The lowest values of the flux occurred at noon and were around 2 – 2.5 µmol $m^{-2}s^{-1}$ while the nighttime values reached approximately 6 µmol $m^{-2}s^{-1}$. The standard deviation of the vertical wind velocity (σ_w) however was very similar overall the 4 summers, being very low at night and having the peak at midday. It can be seen in Figure 7 that σ_w is higher in 2009 and 2010 (with peaks reaching 0.19 ms^{-1}) than in 2007 and 2008, when the peaks were around 0.16 ms^{-1}. During the summer of 2007 the daily CO_2 flux pattern was very variable, with a lot of spikes especially during nighttime. In 2008 the CO_2 flux pattern was constant during the daytime (being approximately 2.5 - 3 µmol $m^{-2}s^{-1}$, the same value as the mid-day CO_2 flux in the summers of 2009 and 2010) but also very variable during nighttime. The nighttime variability can also be seen during the daily cycles in the summers of 2009 and 2010, even if this variability is not so pronounced as in the other 2 years. One possible explanation regarding the nighttime variability is the low and intermittent turbulence that determines spikes in the measured flux values. CO_2 fluxes recorded under very low turbulent conditions (σ_w<0.07 ms^{-1}) were excluded from the dataset used in this study. As a consequence, the remaining nighttime data (that satisfy this turbulence criterion) can be very scattered.

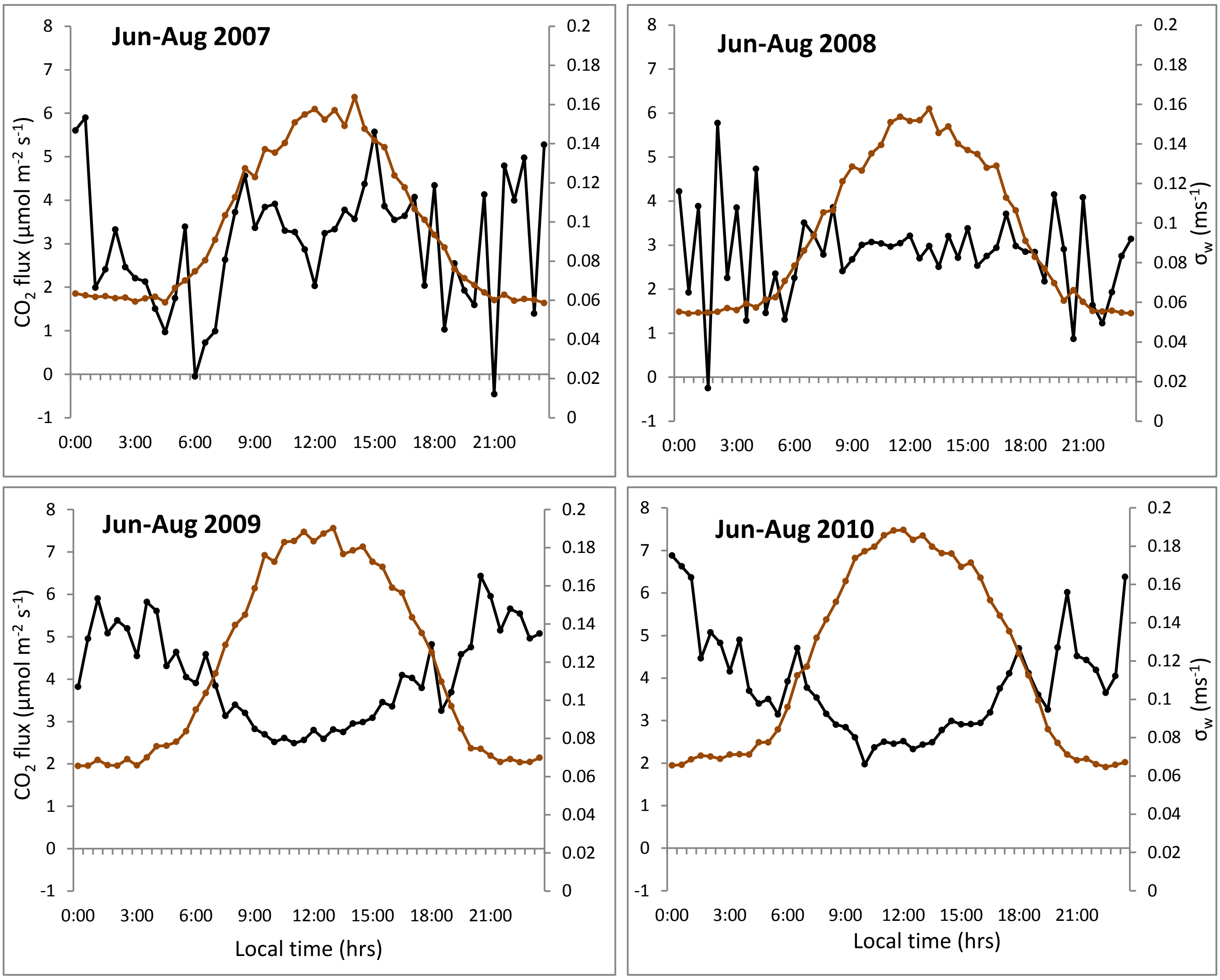


Figure 7: Diurnal cycle (half-hourly averages) of summer (June-August) under-canopy CO_2 flux and the standard deviation of the vertical wind speed (σ_w), measured with EC at 1.5 m height. Brown line represents σ_w and black line CO_2 flux.

The diurnal summer cycle of CO_2 flux and σ_w for 2007 and 2008, without excluding the CO_2 flux measured under low turbulence (σ_w<0.07 ms^{-1}), is presented in Figure 8. In this case, in 2007 CO_2 flux still showed a big diurnal variability, with an important decrease in value early in the evening (the flux gets negative). On the other hand, the exclusion of the turbulence criterion for 2008 data determines a more uniform pattern of the daily CO_2 flux, which gets positive all over the day and averages approximately 2.5 µmol $m^{-2}s^{-1}$.

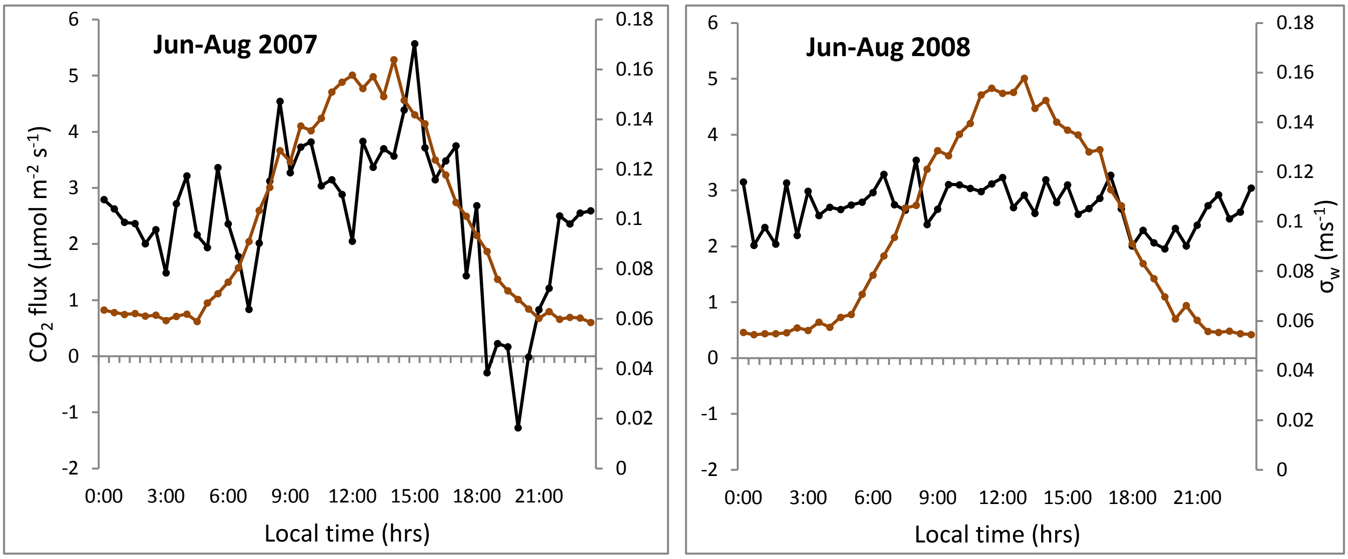


Figure 8: Diurnal cycle (half-hourly averages) of 2007 and 2008 under-canopy CO_2 flux (without applying the σ_w<0.07 ms^{-1} turbulence criterion) and the standard deviation of the vertical wind speed (σ_w), measured with EC at 1.5 m height. Brown line represents σ_w and black line CO_2 flux.

4.4 Comparison between eddy-covariance measurements and chamber CO_2 flux

A comparison between CO_2 fluxes measured with EC and with soil chambers was performed for the periods where data from the two sources were available (see also Table 2). This comparison shows that EC measurements were underestimating the soil-atmosphere CO_2 exchange measured by chambers. Soil chamber flux was always positive; therefore there was a CO_2 release to the atmosphere. The annual pattern of the chamber flux indicates an increase from spring to summer, when a maximum of more than 10 µmol $m^{-2}s^{-1}$ was reached in August, followed by a decrease until the end of autumn (Figure 9). The EC CO_2 flux followed the chamber flux pattern and this can be seen well in 2009 and 2010.

In 2007 the mean EC CO_2 flux was 2.56 µmol $m^{-2}s^{-1}$ and the mean chamber flux was 6.53 µmol $m^{-2}s^{-1}$, the EC flux showing a high temporal variability. In this period EC flux represented on average 39% of the soil chamber flux. Because the chamber measurements stopped in the summer of 2008, only one month period is available for the flux comparison for this year. In May 2008 the mean EC flux was 1.44 µmol $m^{-2}s^{-1}$ and the mean chamber flux 3.26 µmol $m^{-2}s^{-1}$, with EC flux representing on average 44% of the chamber flux. In May, June and July 2009 the average EC flux was 2.45 µmol $m^{-2}s^{-1}$ and the average chamber flux 4.67 µmol $m^{-2}s^{-1}$, with EC representing 52% of the chamber flux. The mean values for August – November 2009 were 3.26 µmol $m^{-2}s^{-1}$ for EC and 6.67 µmol $m^{-2}s^{-1}$ for chambers (EC flux being on average 49% of the chamber flux) and for June - November 2010 3.05 µmol $m^{-2}s^{-1}$ for EC and 7.06 µmol $m^{-2}s^{-1}$ for chambers (EC flux being on average 43% of chamber flux) (Figure 9). As a result it can be seen that EC flux represents between 39 and 52% of the chamber flux and the proportion does not vary much between the studied periods.

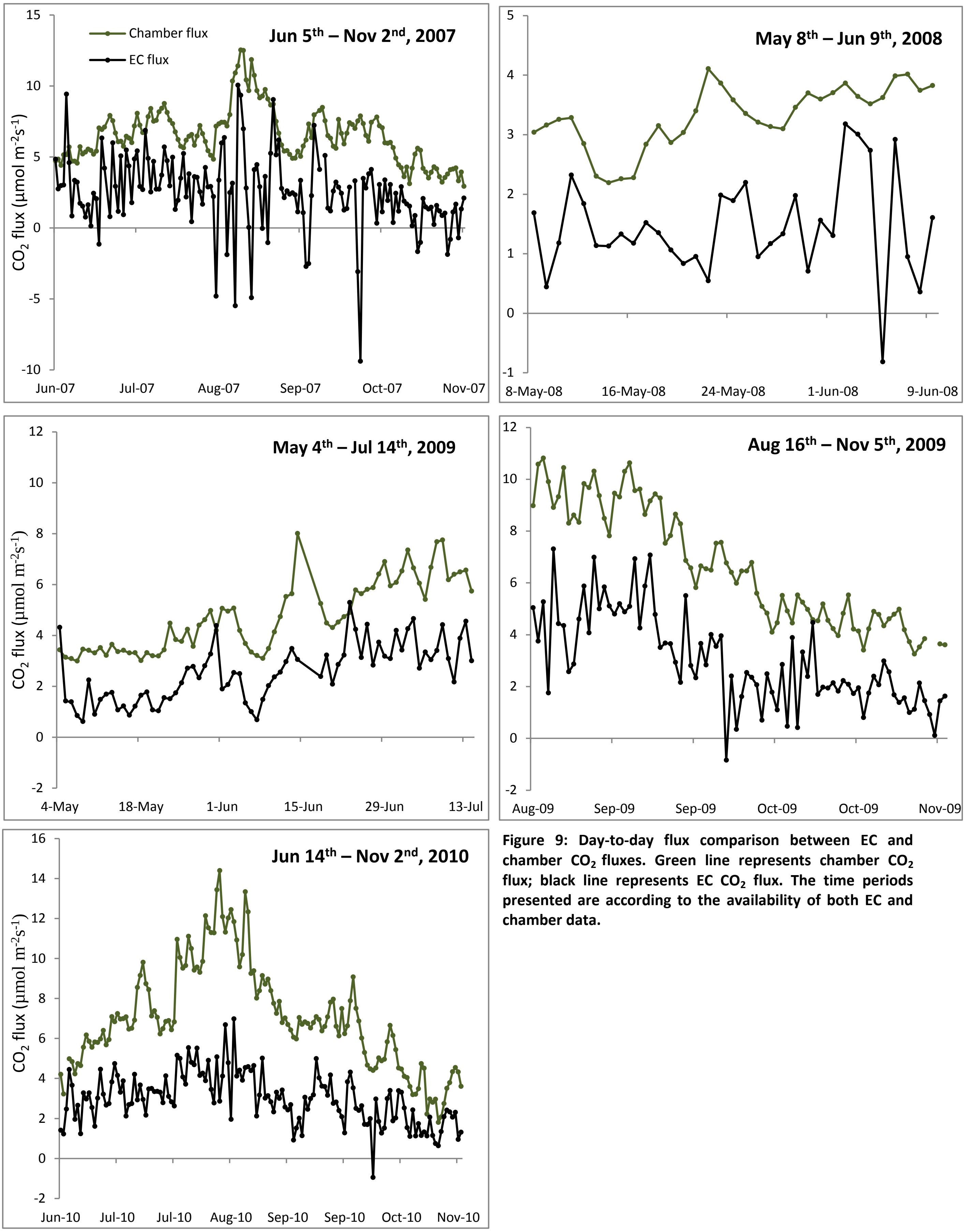
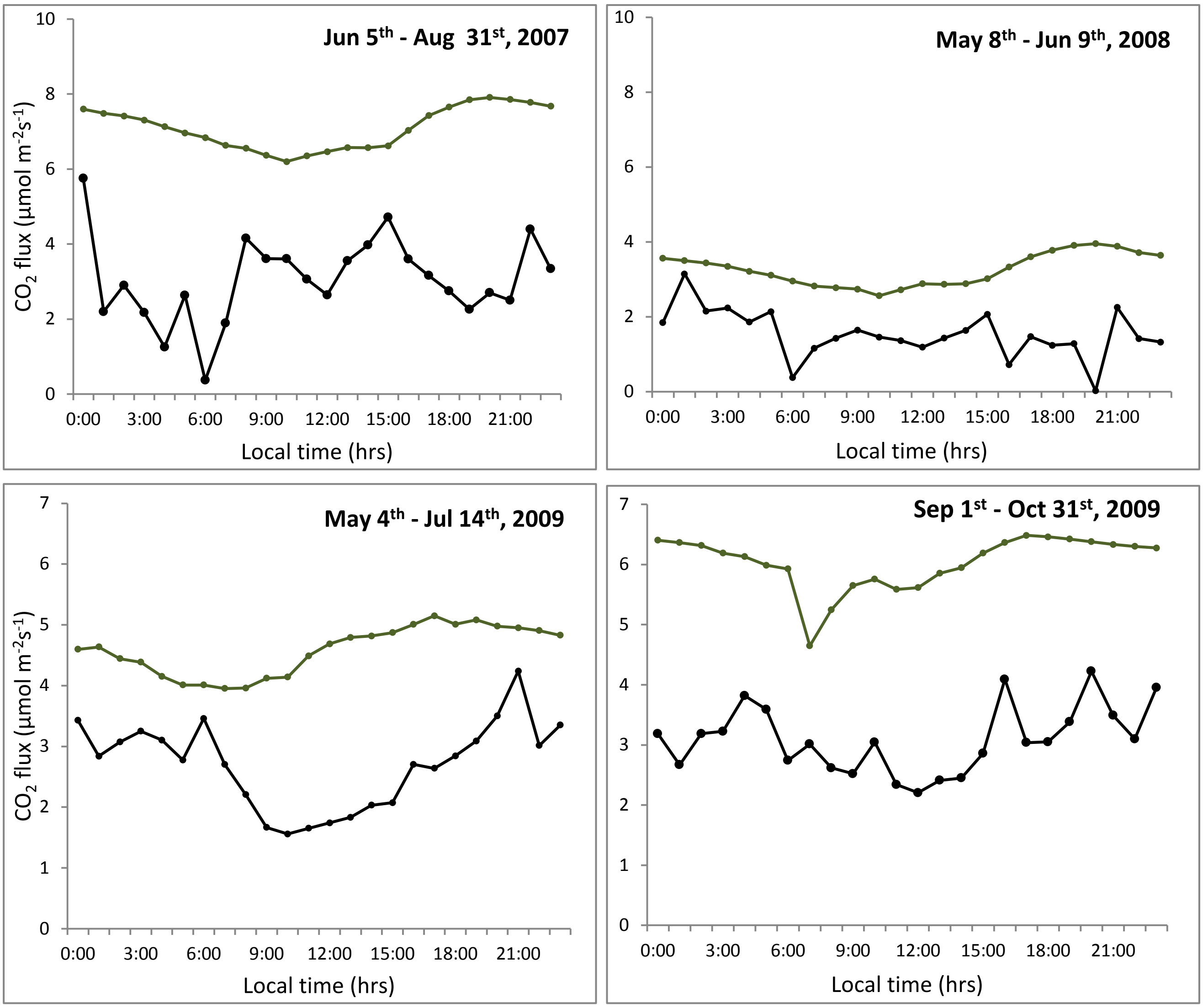


Figure 9: Day-to-day flux comparison between EC and chamber CO_2 fluxes. Green line represents chamber CO_2 flux; black line represents EC CO_2 flux. The time periods presented are according to the availability of both EC and chamber data.

The diurnal cycles of EC and soil chambers CO_2 fluxes for 5 selected periods are presented in Figure 10. The daily cycle of chambers CO_2 flux showed little variability in time and a similar pattern for all the periods, with a minimum daily value in the first part of the daytime (between hours 9 and 12). An exception is the period September – October 2009, where the daily minimum CO_2 flux value occurred very early in the morning, around 7:00. In this period the daily decline in chamber flux was not so visible compared to the other periods, maybe because of decreasing photosynthesis during the autumn season. In May – July 2009 the minimum chamber flux occurred early in the morning (before 9:00) and was followed very soon by the minimum daily EC flux. In 2007 and 2008 the EC flux daily pattern does not match with the chamber flux mainly because of the big variability of the EC data. However, the summer daily pattern of chamber fluxes is followed well by the EC pattern during the summer of 2010.

In the summer of 2007 the EC flux represented 46% of the chamber flux and in May-June 2008 around 44%. In May-July 2009 EC flux was around 52% of the chamber flux, in September and October 2009 approximately 49% and in the summer of 2010 around 39% (Figure 10).



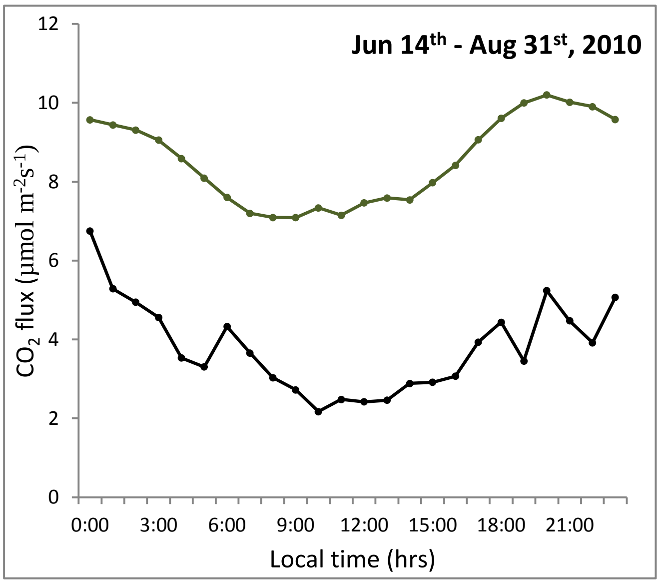


Figure 10: Diurnal cycles (half-hourly averages) for EC and chamber CO_2 fluxes. Green line represents chamber flux and black line EC flux.

5. Discussion

5.1 The use of eddy-covariance method above a forest floor

When analyzing the CO_2 flux and the daily evolution of σ_w it can be observed that at very low vertical wind speeds the CO_2 flux values became more scattered (Figure 1). The daily patterns of σ_w showed very low values during nights and a peak around noon, that was around 0.16 – 0.18 ms^{-1} (Figure 7). The turbulence criterion used in this study was related to a threshold value of 0.07 ms^{-1}, below which data were considered to be recorded under low turbulent conditions. Black et al. (1996) used under-canopy σ_w values lower than 0.15 ms^{-1} for excluding associated EC data. However, in that case only 10% of the data satisfied this criterion (Black et al., 1996) and by applying the same value (0.15 ms^{-1}) as turbulence threshold in this study will also cause too many data to be excluded (see Figure 1). A σ_w value of 0.07 ms^{-1} was considered more appropriate in this case.

Because turbulence is weaker during nights, the application of the turbulence intensity criterion determined mostly nighttime data to be excluded from the raw dataset. As a result, nighttime CO_2 flux showed a big variability, with more spikes compared to daytime flux (Figure 7). It is important to notice that turbulence close to the forest floor was on average higher in 2009 and 2010 compared to the previous years (higher values of σ_w), a consequence of the forest thinning that created a more open environment at this level. Thus, the nighttime CO_2 flux from 2009 and 2010 showed less variability. Excluding the turbulence criterion for 2007 summer dataset still left the CO_2 flux very variable in time (Figure 8). Therefore the variable pattern of the flux was mostly influenced by the use of an open-path EC system. Regarding the 2008 summer dataset, by not applying the turbulence criterion showed a flux pattern that was less variable in time. In this case, the influence of the criterion on the flux pattern was more important than the type of EC system used (in this case, a closed-path system).

Another important issue related to the use of the EC method is related to the spectral corrections in the high frequency range. The correction used in this study is based on the article published by Moncrieff et al. (1997). The authors' method for the spectral correction is purely mathematical and it is based on the co-spectral model by Kaimal et al. (1972). In this method, transfer functions are created in order to correct the fluxes. The method for spectral correction proposed by Ibrom et al. (2007b) is an in-situ method that is designed to correct the low pass filtering effects in the fluxes measured by typical closed-path EC systems (Ibrom et al., 2007b). For the 2008 dataset, both methods showed higher fluxes than in the case of uncorrected EC data and the Moncrieff et al. (1997) method gave higher flux values than the method proposed by Ibrom et al. (2007) (Figure 2).

In a sub-canopy layer, where turbulence statistics and spectral characteristics behave differently from the normal boundary layer conditions, neither the transfer function nor the in-situ methods are necessary reliable (Launiainen et al., 2005). Both approaches have drawbacks. The transfer function approach is based on an ideal co-spectra model which might not be valid in real field conditions. Moncrieff et al. (1997) method is suited for open-path systems and also for closed-path ones, if the tube is heated and it is not too long (Eddy Pro 4.1, Li-Cor Inc., 2012 user guide). The heating of the tube will cause a decrease of the relative humidity inside it; under high relative humidity and strong winds the EC systems show high dampening of fluctuations (Ibrom et al., 2007b). In this project, the tube for the closed-path analyzer was long (16 m) and was not provided with a heating source. Therefore there is an uncertainty in the application of Moncrieff et al. (1997) method.

On the other hand, the method proposed by Ibrom et al. (2007b) might be difficult to implement in this case because the study where this method was proposed was not made under a forest canopy. It is necessary to test the method above the forest floor and to see if the results are accurate. It is worth to mention that in this study both spectral correction methods increased the values of the fluxes up to almost 10%. However, when considering the real value of the difference between the uncorrected and the corrected EC data it can be noticed that it is not large (also the fluxes have small values, especially the energy fluxes) and cannot substantially modify the fluxes signs and patterns. The use of a correct method to perform spectral corrections is a challenging and difficult job and it received special attention in studies that were made under the forest canopies (e.g. Launiainen et al. 2005, Baldocchi et al. 2000). It is important to stress that spectral corrections in the high frequency range represent an important topic for the studies related to EC above the forest floor. Further work is necessary in order to improve the application of these corrections and therefore to increase the quality of the calculated EC fluxes.

A check of the energy balance closure is a good method to verify the accuracy of the EC energy fluxes (H and LE). Under-canopy above-ground EC studies have assessed the closure of the energy balance and some results showed a closure of 84% for a deciduous forest (Baldocchi and Meyers 1991), 70-88% for a ponderosa pine forest (Law et al., 1999a) and 55% for a boreal pine forest (Launiainen et al., 2005). The closure percentage showed seasonal and daily variation. The energy balance closure is difficult under a forest canopy because the measurements of net radiation (R_n) are affected by the multitude of shaded and sunny areas. In this study the energy balance closure was not performed. In general G and storage (S) terms in the energy balance equation are omitted because of their low values compared to H, LE and R_n (especially if the closure is made for above-canopy EC data). However, in the case of under-canopy energy balance check, G needs to be included in the equation because, even if it has low values, it might represent an important part of R_n since the other energy fluxes (H and LE) have low values, as well. S can be neglected for above-ground energy balance closure (since the measurement height is low), but the inclusion of heat storage in biomass can contribute to a better closure above the forest canopy (Lindroth et al., 2010).

5.2 Energy fluxes (H and LE) analysis

H and LE make up a big proportion of the net radiation (R_n). Lee and Black (1993) calculated that the sum of H and LE fluxes beneath the canopy of a coniferous forest of Douglas-fir trees accounted for 74% of the available energy flux. Therefore there is an imbalance in the energy closure and this leads to an uncertainty in the values of the EC energy fluxes above the forest floor. However, even with this degree of uncertainty, by comparing the values of H and LE with other studies a relevant analysis can be performed and at the end some conclusions can be drawn.

Turbulent energy fluxes measured above the forest floor showed a clear annual pattern (Figure 3). The high summer values are determined by a higher R_n in this season. At the beginning of autumn, the decrease in R_n leads to a decrease in H and LE, both fluxes getting close to zero in October. The measured values of the energy fluxes were between 18 and 48 Wm^{-2} for LE and much lower (less than 10 Wm^{-2}) for H. A similar annual pattern of H and

LE can be found in the study of Launiainen et al. (2005) performed at Hyytiälä station, in central Finland, in a similar ecosystem type as Norunda (boreal coniferous forest). However, the measured values of the fluxes differ from the ones in this study. In Hyytiälä, the maximum values of LE reached 100 Wm^{-2} in July, while for H the maximum was recorded in late May and it was around 80 Wm^{-2} (Launiainen et al., 2005). The difference might partially come from the fact that Norunda forest is less open than the Hyytiälä forest. Leaf area index (LAI) in Norunda was 4-5 m^2m^{-2} before the thinning, while in Hyytiälä it was around 3 m^2m^{-2} (Aubinet et al., 2000). The energy fluxes at the soil surface scale inversely with LAI (Baldocchi et al., 2000) because more radiation is absorbed by the canopy if the LAI is large. As a consequence, H and LE measured at Hyytiälä can be higher than the ones measured at Norunda because of the different LAI of the two forest patches. However, after the thinning performed at the end of 2008, the LAI at the measurement area in Norunda decreased to around 2.7 m^2m^{-2}, which is approximately equal to the LAI of Hyytiälä forest. Therefore the difference in LAI cannot explain the difference in the fluxes values between sites, for 2009 and 2010.

By analyzing the annual patterns of H and LE it can be seen that the measured values of LE and H were different for the four studied years. In 2007 an open-path EC system was used and the values of the LE flux were bigger than the ones measured with a closed-path EC system between 2008 and 2010. The difference in LE flux values can be due to different instrumental setup. As an example, closed-path systems attenuate the frequencies inside the tube and consequently they might have a larger spectral loss than the open-path systems. On the other hand, open-path gas analyzers are more affected by weather conditions, like precipitation droplets that stick to the instrument, thus there is an influence on the measured LE flux. These deficiencies can be overpassed by applying a spectral correction to the raw EC data and by verifying the diagnostic values of the instrument. However, under the forest canopy the available spectral corrections are not entirely reliable and a more detailed study is needed for describing a proper spectral correction above a forest floor. The instrument diagnostic values were verified for the open-path gas analyzer and the bad quality data were removed. However the application of the selection criteria might still leave some wrong flux values in the dataset, values that should be regarded and interpreted with caution when analyzing the final results.

The difference between the measured values of H and LE in 2008 and in 2009-2010 can be due to the thinning of the forest. Before the forest thinning, the canopy absorbed most part of the R_n and the radiative exchange at the forest floor was low (visible for H in 2007 and 2008 and for LE in 2008). The forest thinning allowed more radiation to penetrate through the canopy and reach the ground surface, since thinning reduced the LAI value. It can be seen in Figure 3 that the LE flux was higher in 2009 compared to 2008, after the thinning was performed. At the same time, mean daily H flux became slightly positive during summertime, after being mostly negative during 2007 and 2008. The different values of the energy fluxes between the years could also be a result of differences in climate (precipitations, temperatures). However in this study the climate data for Norunda were not analyzed.

The analysis of the diurnal pattern of the energy fluxes shows some more interesting aspects. Both H and LE followed the same daily pattern for the four summer periods (Figure 5). Daily H flux is almost zero during 2007 and 2008. In 2009 and 2010, after the forest thinning, summer H flux became positive in the morning and reached the peak around noon, followed by a sudden decrease in the afternoon, when the flux became negative. LE flux had a peak around noon (2008 - 2010) or a few hours later (2007) and it remained positive throughout the day. Launiainen et al. (2007) found also a very small H flux in the Hyytiälä forest trunk space and as a consequence there was a relative uncertainty in the flux values and signs. Another study, performed by Launiainen et al. (2005) analyzed the summertime daily variation of H and LE under the forest canopy at Hyytiälä, Finland. Their results also showed that under-canopy LE was bigger than H and both fluxes reached the maximum around noon (H approximately 30 Wm^{-2} and LE approximately 45-50 Wm^{-2}). Both fluxes were positive throughout the daytime and close to zero during nights (Launiainen et al., 2005). Daily LE in the summers of 2009 and 2010 were close to the pattern and the values of LE measured by Launiainen et al. (2005), but their measured H was higher than at Norunda. The drop of H in the afternoon (visible in 2009 and 2010) which caused H to be negative before evening is not encountered in other studies related to energy exchange at forest floor (e.g. Launiainen et al., 2005, Baldocchi et al., 2000, Baldocchi and Vogel, 1996). The negative H in the afternoon might be determined by the fact that the canopy temperature at this time of the day is higher than the soil temperature because of the radiation absorption. As a consequence there is a heat flux directed towards the ground. However, this explanation needs to be considered with care, because the afternoon fall in H flux value was not observed in 2007 and 2008.

Baldocchi et al. (2000) measured summertime energy exchange processes at the floor of a heterogeneous and open ponderosa pine forest and of a homogeneous and dense Jack pine forest. Both of them have lower LAI than the forest in Norunda (1.5 for ponderosa pine and 1.9-2.3 for Jack pine forest). The H and LE diurnal patterns showed a peak around noon and values close to 0 during nights; the maximum values were bigger than in Norunda, 150 and 30 Wm^{-2} (H and LE for ponderosa pine) and 75 and 25 Wm^{-2} (H and LE for Jack pine) (Baldocchi et al., 2000). It can be seen in this case that H flux was higher than LE (opposite from Norunda case) and this is because of a more open forest canopy, but also because lower precipitations caused a reduced LE flux. However, during days with precipitations, LE became higher than H (Baldocchi et al., 2000).

Constantin et al. (1999) measured energy and CO_2 fluxes at 2.5 m above the forest floor at Norunda during growing season in 1994 and 1995 (May to early July). They also found a small H flux which had a maximum around 20-30 Wm^{-2} on sunny days and it was very small and negative during nights. In the same time, LE was twice the H and reached maximum values of 80 Wm^{-2}, with almost no flux at nights (Constantin et al., 1999). Their values were larger than the values of H and LE measured in the present study. However it can be noticed than EC H flux was smaller than the LE and the same relationship was found in this project.

Baldocchi and Vogel (1996) measured energy fluxes above the floor of a temperate deciduous forest and of a boreal jack pine forest in the summers of 1992 and 1993. The energy fluxes (H and LE) above the forest floor of the deciduous forest were about half of the ones measured above the floor of the boreal pine forest and the daily patterns showed higher LE than H. The maximum values were recorded around noon and were approximately 50 and 40 Wm^{-2} (LE and H for boreal forest) and approximately 25 and 5 Wm^{-2} (LE and H for deciduous forest) (Baldocchi and Vogel, 1996). The H and LE diurnal cycle from the present study at Norunda resembles more the diurnal cycle measured above the floor of the temperate deciduous forest, while in the case of the boreal jack pine forest the daytime H is much higher, being close to the values of LE (Baldocchi and Vogel, 1996). One explanation of the difference can be the fact that the LAI of the temperate forest (4.9, very similar to LAI at Norunda before thinning) is much higher than LAI of the boreal jack pine forest (around 2) and consequently a bigger portion of the incoming radiation is available at the ground floor of the boreal jack pine forest. As a parallel, the same explanation can be valid for Norunda case, which has lower fluxes than the boreal jack pine forest.

5.3 Under-canopy CO_2 flux and comparison between eddy-covariance and chamber methods

Summer diurnal flux of CO_2 measured with EC was different for the four studied years. The average daytime CO_2 flux was around 2.5 – 3 µmol $m^{-2}s^{-1}$ in the summers of 2008, 2009 and 2010, while in the summer of 2007 it was slightly higher and more variable in time (Figure 7). The summer nighttime flux reached values of around 6 µmol $m^{-2}s^{-1}$. In 2009 and 2010 a lower CO_2 flux during the daytime can be clearly seen due to understory photosynthesis below the EC measuring point, sustained by the thinning of the forest. The daily minimum of CO_2 flux cannot be observed in 2007 and 2008. The summer EC CO_2 flux measured in this study was bigger than the CO_2 flux measured by Constantin et al. (1999) during a 4 day period in July 1995 at Norunda. The authors measured at 2.5 m height nighttime flux rates of 1.9 ± 1.1 µmol $m^{-2}s^{-1}$ and daytime rates between 0.45 and 0.9 µmol $m^{-2}s^{-1}$ (Constantin et al., 1999). The difference might be partially explained by the fact that the location of the under-canopy tower from the study of Constantin et al. (1999) was mounted 150 m south-east from the main Norunda EC tower. In this case there are differences in the EC footprint areas of the two studies. Another explanation for the difference comes from the different instrumentation used (a LI-6262, Li-Cor Inc., Lincoln, NE, USA gas analyzer).

Launiainen et al. (2005) found under-canopy summertime CO_2 flux in Hyytiälä (measurements at 3 m height) with minimum values of 1.5-1.7 µmol $m^{-2}s^{-1}$ at midday and maximum values of 2.4-2.5 µmol $m^{-2}s^{-1}$ in the late evening. The flux values in this Norunda study are higher than the ones measured at Hyytiälä. The authors also found a minimum in the EC CO_2 flux early in the morning, followed by a rapid increase that can be determined by CO_2 accumulation during nighttime followed by a sudden release with the turbulence onset at the beginning of the day (Launiainen et al., 2005). In this study a morning minimum can be seen in 2007, 2008 and 2010 (Figure 7). However the very scattered data in 2007 and 2008 makes the occurrence of this minimum uncertain, being possibly determined by the very noisy EC signal. On the other hand, the low height of the measurements (1.5 m) makes the impact of the CO_2 accumulation on the flux diurnal pattern uncertain.

Law et al. (1999a) studied the below-canopy CO_2 flux in a ponderosa pine forest ecosystem characterized by a very open canopy. Their results showed that during the months of March, May and August the daily patterns of CO_2 flux were behaving in the same manner, with maximum values of below 2 µmol $m^{-2}s^{-1}$ in March, around 3.5 µmol $m^{-2}s^{-1}$ in May and above 4 µmol $m^{-2}s^{-1}$ in August (Law et al., 1999a). During these three months the midday minimum was not found and the flux increased in the afternoon together with an increase in soil temperature. However, a midday minimum occurred during July, where photosynthesis determined a CO_2 flux of around 0.5 µmol $m^{-2}s^{-1}$ just before noon (Law et al., 1999a). The midday minimum was not found for the under-canopy EC measurements of CO_2 flux in a deciduous and a boreal jack pine forests from the study of Baldocchi and Vogel (1996). The authors calculated peaks in summertime CO_2 fluxes of 4 µmol $m^{-2}s^{-1}$ for boreal jack pine forest and of 3 µmol $m^{-2}s^{-1}$ for deciduous forest. The lack of midday minimum could be an effect of the more closed canopies of the forests and therefore of low understory photosynthesis. In the present Norunda study the midday minimum was not encountered in 2007 and 2008. This can also be due to low understory photosynthesis during these two years, before the forest thinning.

The comparison between CO_2 fluxes measured with EC and with soil chambers showed that EC flux was lower than soil chambers flux. EC flux accounted for 39 to 52% of the chambers flux, for each period where the two fluxes were compared. The distance between the EC tower and the soil chambers area was approximately 50 m. If the results of the footprint estimations from Launiainen et al. (2005) and Law et al. (1999a) are taken into consideration, which show that for 2-3 m height EC measurements 80-90% of the flux comes from less than 50 m distance from the measurement system, it can be estimated that in this study the chambers were located at the edge of the EC footprint area. However, the soil type and vegetation were similar for both EC and chamber locations and the comparison of the two methods can be relevant.

In general, the EC flux followed the trend of the chambers flux. This feature is more difficult to see in 2007 because of the very scattered EC data. Higher similarities between patterns can be observed during the periods August – November 2009 and June – November 2010 (Figure 9). As expected, the maximum fluxes (both EC and chambers) occurred during summer season, followed by a strong decrease during autumn. The daily pattern of soil chambers flux showed a minimum early in the morning, followed by an increase in the afternoon (Figure 10). The afternoon increase could be a result of higher soil temperatures that generate a stronger soil respiration.

A discrepancy between EC flux and soil chambers CO_2 flux has been found in other studies as well. Launiainen et al. (2005) found that EC CO_2 flux measured at Hyytiälä, Finland, accounted on average for 59 to 62% of the soil chambers flux for the summer season (July – August). Law et al. (1999b) compared nocturnal EC measurements above the forest canopy with scaled-up chamber measurements and they found that EC estimates were lower than chamber estimates by 50%. Lavigne et al. (1997) also reported lower nocturnal EC flux compared to scaled-up chamber measurements. Norman et al. (1997) compared chambers CO_2 flux with EC flux measured at 2 m height above the floor of a boreal jack pine forest but the results were different and inconsistent between the study periods. On the other hand, Law et al. (1999a) found similar below-canopy EC and soil chamber fluxes during a 20 day period in July 1996, both fluxes showing also a similar daily cycle for the same period.

One reason for the difference in flux values between EC and soil chambers might come from the fact that especially during nights the EC CO_2 flux is underestimated as a result of CO_2 accumulation and drainage below the measurement point. However in this study there was a very low height for the EC measurements (1.5 m) and the CO_2 accumulation effect is uncertain. Moreover, the application of the turbulence criterion in this study excluded a big amount of the nighttime data. Another source of flux underestimation in EC is the spectral loss. Launiainen et al. (2005) calculated that in the Hyytiälä study the high-frequency CO_2 transport associated with small-scale eddies can induce a maximum 10% underestimation of the total exchange rate of CO_2, therefore this underestimation can explain only partially the difference between methods. In this project the spectral loss for the closed-path EC system might also determine an underestimation of the EC flux and consequently a difference between EC and chamber methods. This difference between the two measurement methods is also due to the fact that the soil CO_2 flux measured by chambers is very heterogeneous and shows a large spatial variability. EC method measures CO_2 flux from the whole footprint area and it includes photosynthesis taking place below the measurement point, while the chamber show only the flux values from the particular point of measurement.

5.4 Possible developments of the project

This project was performed for the purpose of reaching the main research objective of the study. However, the big amount of data and the time limitations allowed only a limited assessment of the applicability of EC method under a forest canopy and the analysis of the energy and CO_2 fluxes was carried out only to a certain extent. As a result, there are more additional things that can be done in order to improve the quality of the present study and to broaden the understanding of the exchange processes under the forest canopy at Norunda site. Among the possible future developments of this project, that can be mentioned, are:

- The energy balance closure needs to be verified under the forest canopy. The difficulty arises from the measurement of the R_n, which is affected by the heterogeneous environment beneath the canopy. However, even if it is very unlikely to come to a perfect energy balance closure, this check could be very important for the assessment of the quality of the EC measured fluxes, H and LE. The results need to be interpreted with caution and having in mind other studies performed in similar environments.
- The corrections applied to the EC raw data need to be deeply analyzed. Among the corrections, an important source of uncertainty is related to the spectral corrections, and especially to the spectral loss in the high frequency range, since at low heights above the ground the small eddies are dominant. In this study only a short comparison between uncorrected fluxes and two spectral correction methods was made, due to time and complexity limitations. The corrections were pre-defined and directly applied in the Eddy Pro software. For a higher confidence in the values of the fluxes the spectral characteristics of the under-canopy environment at Norunda need to be studied in detail.
- A big amount of nighttime data was excluded because of low turbulence. At the same time, the set of the turbulence criterion is a matter of debate. The nighttime CO_2 fluxes that are discarded in this study could be gap-filled with values calculated based on nighttime CO_2 flux measured under turbulent conditions and its relationship with a determining parameter, like soil temperature. In this way, by having more nighttime data the EC fluxes will not be so variable and scattered.
- A comparison between under-canopy and above-canopy EC data will be very interesting and useful in understanding the magnitude and the dimensions of energy and CO_2 fluxes at different levels of the boreal forest ecosystem.

6. Conclusions

The analysis of four years of data and the comparison of EC and soil chamber methods show that EC can be used for measuring fluxes of energy and CO_2 above the ground of a boreal forest. However there are some difficulties in implementing the method and the results must be interpreted with care. The intermittent nature of turbulence under the canopy and its big proportion in the high frequency range are challenging for scientists that need to choose an appropriate instrumentation setup and corrections applied to the raw data. In the same time, the calculated fluxes can have small values and show a big variability in time. Together with the chamber method, EC provides information about the values and the patterns of soil–atmosphere exchange processes above the forest floor. However, EC method gives a time evolution of the fluxes, representative for the footprint area, while soil chambers give more information about the spatial variability of the CO_2 flux.

The main conclusions of this study are related to the research questions mentioned in the Introduction part and are according to the research objective of this master thesis, i.e. to increase the knowledge about the applicability of the EC method above the floor of a boreal forest. The conclusions can be summarized as follow:

- Under-canopy energy fluxes (H and LE) had a clear annual pattern, with the highest values during summer season and the lowest values in autumn. H values were low throughout the study periods. Annual maximum daily average LE values were between 18 and 48 Wm^{-2}. The summertime diurnal patterns of H and LE showed a maximum of LE around or soon after noon and a low H flux, mostly negative during 2007 and 2008. In the summers of 2009 and 2010 daily H was positive until afternoon, after which became negative. Maximum summer LE flux was between 29 and 50 Wm^{-2} and maximum summer H reached 10 Wm^{-2} in 2009 and 2010. The open-path system showed higher and more scattered values of LE. In 2009 and 2010 the energy fluxes had higher values than in 2008, one reason being the thinning operation of the forest that allowed more available energy at the ground level. The measured energy fluxes are lower than in other studies performed under the canopy of boreal forests but the daily patterns have similar shapes. The differences might partially be explained by the more closed canopy at Norunda and partially by differences in climate between ecosystems. The decrease in LAI after thinning in the autumn of 2008 increased the values of H and LE. However, the measured values of H still remain low in comparison with other studies.
- CO_2 flux measured by EC also showed a clear annual pattern, with highest values recorded in August or at the beginning of September. The annual average CO_2 flux had values between 2.5 and 3 µmol $m^{-2}s^{-1}$. In 2007, the open-path EC system gave more scattered results for the CO_2 flux compared to the other years, as in the case of energy fluxes. The summer daily pattern of CO_2 flux showed a big variability for the nighttime data. Therefore, the large variability of the CO_2 flux was caused by both the removal of values recorded under very low turbulent conditions (σ_w<0.07 ms^{-1}) and the use of an open-path EC system. The summer daytime flux was fairly constant in 2008; in 2009 and 2010 a daily minimum was observed, that occurred around noon. This minimum is due to photosynthesis inside the EC footprint area, enhanced also by the thinning of the forest.
- The comparison between EC and chambers CO_2 fluxes showed that both fluxes followed the same pattern, but there was a discrepancy between the recorded values. EC flux represented between 39 and 52% of the chambers flux, the percentage being

different between the studied periods. The difference between EC and soil chambers CO_2 fluxes is consistent with other studies. Among the reasons for this difference, that can be mentioned, are: loss of nighttime fluxes by EC under low turbulent conditions; spectral loss of CO_2 flux for the high frequencies of the eddies dominant at small heights above the ground; chambers were located at the edge of the EC footprint area; EC measurements represent an average flux for the entire footprint area, while chambers provide the flux values for the particular spot of measurements and show a very large spatial variability.

- Further improvements of this project can be performed in order to increase the accuracy and the reliability of the under-canopy EC fluxes. Spectral corrections need to be analyzed in more detail and energy balance check at the ground level will provide a good criterion for the assessment of the EC energy fluxes. In the same time, an analysis of above- and below-canopy EC fluxes will show the exchange processes at different ecosystem levels. The nighttime CO_2 flux is also important because some different treatment of the flux could determine less exclusion of the data recorded under very low turbulent conditions.

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