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Multiple quality tests for analysing CO_2 fluxes in a beech temperate forest

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Abstract

The eddy covariance (EC) measurements are widely used to estimate the amount of carbon sequestrated by terrestrial biomes. The data quality and the selection of the correct EC records become an important step in the CO_2 flux determination procedure. In this paper an innovative combination of existing assessment tests is used to give a relatively complete evaluation of the net ecosystem exchange measurements. For the 2005 full-leaf season at the Hesse site, the percentage of bad quality data is relatively high (59.6%) especially during night-time (68.9%). This result strengthens the importance of the data gap filling method. The filtering used does not lead to a real improvement of the accuracy of the relationship between the CO_2 fluxes and the climatic factors. The soil respiration spatial heterogeneity (on a site with relatively homogenous vegetation pattern) seems to be too important to allow this improvement. However, the data rejected present some common characteristics. Their removal lead to a 10% increase in the total amount of CO_2 respired and photosynthesised during the 2005 full-leaf season. Consequently the application of our combination of multiple quality tests is able improve the inter-annual analysis. The question of a systematic application on the large database like the CarboEurope and FLUXNET is legitimate.

1 Introduction

Carbon dioxide exchanges between the terrestrial ecosystems and the atmosphere are of major importance for climate change and therefore for the future of the vegetation (Houghton et al., 1998). The quantification of CO_2 fluxes at the ecosystem-atmosphere interface is one of the primordial steps to improve our knowledge about the ecosystem carbon budget. The eddy covariance (EC) technique (Aubinet et al., 2000) provides the opportunity to have a direct measurement of these fluxes. Sites equipped with EC systems spread around the world (Baldocchi et al., 2001) with, at the present time, more than 400 stations (http://www-eosdis.ornl.gov/FLUXNET), some of them have

been running continuously for more than 10 years. The EC technique is based on high frequency (10–20 Hz) records of wind speed components, CO_2 and H_2O concentrations. The amount of data produced is so large that the detection of instrumental anomalies becomes very difficult. Moreover, the flux determination includes several methodological choices (Finnigan et al., 2003) and requires selection of periods with adequate micro-meteorological conditions (Feigenwinter et al., 2004; Rebmann et al., 2005). All these difficulties lead to errors and propagation of uncertainties that are able to mask some properties of biophysical processes. The improvement of the EC dataset quality has become a real challenge for the EC scientific community (Richardson et al., 2006a; Papale et al., 2006).

One of the problems met with the EC measurements are the short-term net CO_2 flux fluctuations during night-time (Longdoz et al., 2004) without any biophysical explanation. Two reasons have already been identified. The CO_2 produced by the respiration of the ecosystem components can be stored in the canopy air or blown horizontally by advection (Paw et al., 2000). This CO_2 is not registered by the EC system. For our temperate beech forest site (Hesse, France), corrections with canopy air storage measurement and selection of the data without advection (Aubinet et al., 2005) have not completely erased this problem. Consequently, the question of the quality of the data generated by the EC systems arises

Different authors have presented several quality tests for the selection of the EC data (Vickers and Mahrt, 1997; Foken and Wichura, 1996; Göckede et al., 2004) and several methods to fill the gaps produced by this data selection (Falge et al., 2001; Hui et al., 2004; Ruppert et al., 2006). In this study, we combine most of the tests proposed for the CO_2 flux. This innovative grouping is applied to the records from the Hesse site for the full-leaf 2005 season. This period presents some reasonably standard climatic conditions (no extreme events). The duration of the period is short enough to assume relatively stable ecosystem response to environmental factors and long enough to provide a sufficient quantity of data (even after quality tests selection) to analyse these responses. The impact of our relatively complete combination of

quality tests is evaluated by comparison with the datasets including or not including the records incriminated by the tests. The analysis is performed on the relationships between CO_2 fluxes and climatic factors and on the total fluxes accumulated during the full-leaf 2005 season.

2 Material and methods

2.1 Site

All the data used in the present analyses come from an experimental plot located in the state forest of Hesse (48°40′ N, 7°04′ E, North-east of France). This site belongs to the CarboEurope network. The climate is temperate with 950 mm and 10.1°C for mean annual rainfall and air temperature. The stand is composed mainly (90%) of Beech (*Fagus sylvatica*). For the period considered in this paper (full-leaf season from 15 May to 14 October 2005) the trees were 39 years old and 17 m high (mean value), the LAI (5.1 $m^2\,m^{-2}$) and tree density (2916 stem/ha) were relatively low compared to the previous years (mean LAI 7.3 $m^2\,m^{-2}$) because of the thinning performed during the winter 2004–2005. The roughness length was 0.4 m. The gentle slope (approximately 3% going down in the Northeast direction) is sufficient to induce advection during the stable nights (Aubinet et al., 2005). The distance between the EC tower and the forest edge varies from 390 m to 1610 m. The full-leaf season selected (2005) can be qualified as relatively normal when compared to the mean climate of the eight previous years . The mean air temperature is equal (16°C), the total amount of precipitation is slightly lower (381–416 mm) and the cumulative global radiation slightly higher (2957–2873 MJ m^{-2}) for 2005. A more detailed description of the site can be found in Granier et al. (2000a) and Granier et al. (2000b).

2.2 Fluxes measurements

The net CO_2 fluxes between the ecosystem and the atmosphere (*Fc*) were measured with an eddy covariance system composed by a sonic anemometer Solent R3 (Gill Instruments Ltd, Lymington, UK) and an infrared gas analyser Li-Cor 6262 (Li-Cor Inc., Lincoln, NE, USA). The anemometer measuring the three components of the wind velocity and sonic temperature (u, v, w, T) at 20 Hz is located on a tower at 23.5 m above ground. The IRGA measuring CO_2 and H_2O concentrations at 10 Hz is located at the ground level, analysing the air sucked from a sampling point close to the anemometer with an air flow rate of 6 l min^{-1}. A mass flow controller (Model 5850, Brooks, Veenendaal, Netherlands) controls the airflow. The computer acquires the data with the software Eddymeas (Kolle and Rebmann, 2007). To improve u, v and w data, correction for sonic anemometer angle of attack errors is performed (Nakaï et al., 2006). This error becomes significant when the wind vector angle to the horizontal plane is superior to 20° (threshold value depending on the sonic anemometer type). It is provoked by transducers self-sheltering or flow distortion induced by the anemometer frame. For each half-hour, the *Fc* fluxes are calculated from high frequency u, v, w and CO_2 concentration measurements using block averaging operator (Finnigan et al., 2003) and planar fit as coordinates rotation method (Wilczak et al., 2001). Finally, frequency correction applied to *Fc* follows the procedure proposed by Aubinet et al. (2000).

The net ecosystem exchange (NEE) is obtained by the summation of *Fc* and CO_2 storage in the canopy air (Sc). Sc corresponds to the difference between the total amount of CO_2 below the eddy covariance measurement height, at the beginning and the end of the half-hour. This amount of CO_2 is estimated from a profile of concentration estimated from measurements at 6 different heights (22 m, 10.4 m, 5.2 m, 2 m, 0.7 m, 0.2 m). These measurements are performed with an infrared gas analyser Li-Cor 6262 (Li-Cor Inc., Lincoln, NE). For each level, the concentration used for the Sc computation is the average of the values recorded during 10 s after purge. More information about tubing, pumps and filters used are given in Granier et al. (2000b).

2.3 Quality control procedures

The eddy covariance data treatment used in this study includes several tests to control the data quality and detect flux sampling problems. First, following Vickers and Mahrt (1997), the records are flagged to identify abnormalities that may result from instrumental or data recording problems coming from the anemometer or the IRGA (corresponding to hard flag in Vickers and Mahrt). The tests check in the high frequency measurements of wind velocity and CO_2 concentration the presence of spikes, discontinuities of mean or variance, unrealistic data, large higher-moment statistics (skewness and kurtosis) or standard deviation value out of tolerable range. The half-hours *Fc* are flagged when parameters reflecting the importance of these presences exceed threshold values. As proposed by Vickers and Mahrt (1997), the thresholds are empirically adjusted for the Hesse site by inspection of frequency distributions of the parameters. The objective is to flag any records with obvious instrument problems. This threshold determination procedure realised for the Hesse 2005 full-leaf season can be illustrated by the choice of upper limit of the acceptable range for the kurtosis of CO_2 concentration data , which is the more selective test (see results section). The upper limit of the kurtosis is set to 7.9 to be sure to flag the half-hour record like the one presented in the Fig. 1a. Indeed, the kurtosis of this half-hour is 8.1 because of few irregularities (too large to be considered as spikes) that happen at regular interval indicating their instrumental origins. This half hour record has to be flagged. Moreover, we have not found a half-hour with a lower kurtosis and presenting apparent instrumental problem. For example, important intermittent turbulent events (Fig. 1b) can explain a kurtosis slightly lower than the threshold (7.7) and should not be flagged. Contrary to Vickers and Mahrt (1997) all the half-hours flagged have not been individually analysed to verify the origin of the flux-sampling problem. This procedure is not materially feasible when it is applied to large datasets. In consequence it is possible that a few correct fluxes are flagged but this conservative procedure, excluding a maximum of technical anomalies, is preferable (be sure to exclude all the technical anomalies).

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The last test to detect instrumental abnormalities is the verification of the airflow rate in the tubing transporting the air from the sampling point (at the top of the tower) to the EC IRGA. This rate is controlled and measured by a mass flow controller (Tylan 261, Tylan Corporation, Torrance, CA, USA). It is set to 6 l min^{-1} leading to a constant time lag of 4.8 s between *w* and *C* measurement. The flag is activated when the airflow rate is 10% below or above the desired value. This range is chosen because the post-processing programme is able to correct any deviation of the time lag in this range.

The other quality assessment tests do not refer to instrumental abnormalities but verify the stationarity for *Fc* and the inclusion of the *Fc* footprint area in the targeted ecosystem. The stationarity test procedure follows the method presented by Foken and Wichura (1996). The *Fc* value determined for the half-hour period is compared to the mean out of six 5-min *Fc* from the same period. The flag is activated when the difference between both values (due for example to changing weather conditions) is above 30% so when the *Fc* data could not be used for fundamental research (Foken et al., 2004). For the footprint test, the Schuepp model (Schuepp et al., 1990) modified by Soegaard et al. (2003) determines the *Fc* footprint area. The record is flagged when more than 10% of *Fc* is coming from a patch (25 m long, 5° large) located out of Hesse beech forest. The forest edge is determined with the Hesse land use map already utilized in Rebmann et al. (2005).

2.4 Datasets

Two datasets are established both compiling the main micrometeorological variables (global radiation, air and soil temperature, photosynthetic photon flux density, soil water content, air humidity, friction velocity...) and the NEE values for the 7344 half-hours between the 15 May and 14 October 2005. At the beginning of the analysis, in one of the datasets, the gaps in the NEE correspond only to the breakdown and maintenance periods. This dataset is called DSIFR (DataSet Including Flagged Records) in the following. In the other dataset, in addition, the records flagged by the quality tests are removed and replaced by gaps (DataSet Excluding Flagged Records, DSEFR). Two

different dataset partitioning are applied during the analysis. The partitioning between night and day is based on the global radiation (Rg) with night records corresponding to Rg below $3\,W\,m^{-2}$. During night-time NEE corresponds to ecosystem respiration (Reco) and during daytime to the sum of gross primary productivity (GPP) plus Reco. The second division aims at isolating the periods without soil water stress for Reco. As soil respiration represents usually the major part of Reco (Law et al., 1999; Longdoz et al., 2000) and because Ngao (2005) has demonstrated that soil respiration in the Hesse forest is limited by water depletion when soil water content on the first 10 cm (SWC) is below $0.2\,m^3\,m^{-3}$; we have adopted this threshold for the dataset repartitioning.

Different authors (Staebler et al., 2004; Aubinet et al., 2005) have shown that NEE estimated by summation of Fc and Sc can underestimate CO_2 exchanges during periods with low turbulence (low friction velocity u^*). Night-time Reco measurements clearly highlight this underestimation. At constant temperature, Reco drops down when u^* decreases. This observation has no apparent biophysical explanation. At the Hesse site, additional measurements have proven that some CO_2 emitted during night by the ecosystem components goes out of the forest by horizontal advection when air mixing is limited (Aubinet et al., 2005). This CO_2 is not detected by the eddy covariance or profile concentration measurement systems explaining flux underestimation. We have established a u^* threshold below which Reco is not correctly measured by a two steps procedure. In the first step, the temporal variability of Reco, mainly due to temperature fluctuations, is determined. Using data during periods without water stressed, the Reco dependence on temperature is fitted (regression algorithm presented in the following section) using a Q_{10} relationship (Black et al., 1996):

$$R\text{eco} = R\text{eco}_{\text{Tref}} \cdot Q_{10}^{\left(\frac{T-T\text{ref}}{10}\right)} \quad (1)$$

where Q_{10} is the parameter reflecting the temperature sensibility and $R\text{eco}_{\text{Tref}}$ is the Reco value for a reference temperature (Tref). Each half-hour Reco is then divided by $Q_{10}^{\left(\frac{T-T\text{ref}}{10}\right)}$ to obtain a value $R\text{eco}_s$ that should be relatively constant during non water stressed periods. The second step consists in distributing $R\text{eco}_s$ in u^* classes. For

each class, we compute the $Reco_s$ class average $\overline{(Reco_s)_{cl}}$, and the $Reco_s$ averaged on all the data with u^* above the upper limit of the class $\overline{(Reco_s)_{hi}}$. The objective is to detect the classes with a $\overline{(Reco_s)_{cl}}$ significantly lower than $\overline{(Reco_s)_{hi}}$ (comparison procedure described in the following section). Among these last classes, the one with the higher u^* is selected. The u^* threshold corresponds then to the upper limit of this class. Because the Q_{10} relationship fit depend on the available dataset, the u^* threshold determination procedure is applied separately on DSEFR and DSIFR.

2.5 Statistical analysis and regression

All the statistical analysis and non-linear regressions are performed by Statgraphics Plus software (Statistical Graphics Corp., Herndon, VA, USA). The two data sample comparisons are designed to determine whether they are significantly different by running a t-test to compare the means of the two samples. The equality of the variances of the two samples is assumed. ANOVA (F-test) is used for the multi-groups comparison. The non-linear regression algorithm is an iterative procedure, determining the parameters that minimize the residual sum of squares (Marquardt method). The non-linear regressions are used to determine the relationship between meteorological variables and fluxes. For some of the regressions with a single independent variable, it is suitable to reduce the possible impacts of spatial heterogeneity and other variables. Then the regressions are performed with bin-average fluxes where the averages are performed for independent variable classes. The average are weighted with weights proportional to the reciprocals of the squared standard errors (Murtaugh, 2007).

3 Results – discussion

3.1 Quality control results

Among the 7344 half-hours treated, only 2.1% corresponds to total breakdown (mainly electricity failure) or maintenance of the EC system and 2.6% to specific maintenance or bad functioning of the profile sampling system. On the remaining *Fc* data (7190 values), flags are activated on 48.8% of the data (3508 half-hours) consequently on 47.8% of the total period. This is a relatively high percentage but not very surprising compared to the proportion already presented in the literature. Rebmann et al. (2005) flagged 28% of the Hesse *Fc* for the summer 2000 only with the stationarity test. Vickers and Mahrt (1997) flagged during their measurement campaigns one-third of the records with the Haar variance criteria and one-half for too large kurtosis.

In our procedure, the causes of the *Fc* flags could be divided in five categories: anemometer, CO_2 IRGA and mass flow controller malfunctioning, lack of stationarity and too large footprint. The percentages of *Fc* flags due to each category are presented in the Table 1. Two tests appear to be highly restrictive: the stationarity and the CO_2 IRGA anomalies. The stationarity flag percentage is close to that estimated by Rebmann et al. (2005) for the Hesse summer 2000 (28%). To go one-step further in the analysis and according to the Sect. 2.3, we subdivided the CO_2 flag into seven tests: spikes, mean discontinuity, variance discontinuity, absolute limits, skewness, kurtosis and standard deviation. The kurtosis is more selective (Table 2) with flags on 31.9% of the total period (32.6% of non-affected *Fc*). This predominance of the kurtosis test on the other ones has been also observed by Vickers and Mahrt (1997) on their own measurements. The sum of all the half-hours flagged by the different CO_2 tests (3960) exceeds the value given in the Table 1 for the global CO_2 anomalies (2445) because of multi-flagged data. The percentage obtained for the spike test is extremely low. Indeed, the sudden variations in the records are often larger than the maximum width of what can be considered as spike (4 points equivalent to 0.4 s). These variations are taken into account in the higher-moment statistics explaining their relatively

high percentages.

3.2 Friction velocity thresholds

The u^* threshold is determined for the two datasets (DSEFR and DSIFR). The fit of the Q_{10} relationship on the $Reco$ data (night NEE) are performed excluding soil water stress periods (representing 17% of the total period). The bin-average is used to erase the impact of the $Reco$ values affected by horizontal advection. We tested soil temperatures at 10 and 5 cm depth as independent variables. The results of these fits are presented in the Table 3. The 10 cm depth soil temperature (Ts_{10}) is chosen because of its better general aptitude to explain the $Reco$ variations. This is probably due its superior ability to take into account the spatial heterogeneity, because the 10 cm depth soil temperature value is an average of six measurements while the 5 cm temperature is measured with only one sensor. The $\overline{(Reco_s)}_{cl}$ calculated with u^* classes of 0.02 m s^{-1} width, are compared to $\overline{(Reco_s)}_{hi}$. Among the classes giving a $\overline{(Reco_s)}_{cl}$ significantly lower than $\overline{(Reco_s)}_{hi}$, the class with the higher u^* has 0.09 and 0.11 m s^{-1} as lower and upper limits, respectively. This result is valid for the two datasets. For DSEFR, the $\overline{(Reco_s)}_{cl}$ and $\overline{(Reco_s)}_{hi}$ of this class are respectively 2.85 and 4.21 μmol m^{-2} s^{-1} (p-value = 0.0005). For DSIFR, the corresponding $\overline{(Reco_s)}_{cl}$ and $\overline{(Reco_s)}_{hi}$ are 3.45 and 4.86 μmol m^{-2} s^{-1} (p-value=0.001). Consequently, the u^* threshold is set to 0.11 m s^{-1} for the two datasets. This value fully agrees with the one obtained by Papale et al. (2006) for Hesse 2001 and 2002 while the determination method was different (Reichstein et al., 2005). This result suggests that the u* threshold is relatively constant with time. The u^* filter is applied both, during night and daytime (concerning, respectively, 30% and 7.2% of the time) and increases significantly the gap presence in the datasets. The gap fraction, compared to the total period, increases from 50.3% to 59.6% for the DSEFR and from 4.7% to 19.7% for DSIFR. The increase is more important for DSIFR because some half-hours with low u^* are already rejected by at least one of the other quality tests. Even if our conservative way to set the limits for the instrumental malfunc-

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tioning tests can be responsible of a slightly overestimation of the percentage of data removed in DSEFR, this last one is high, especially during night-time (68.9%). This stresses the importance of the data gap filling method (Moffat et al., 2007).

3.3 Ecosystem respiration temporal variability

The temporal variability of *R*eco is usually attributed to temperature and soil water content variation (Carlyle and Ba Than, 1988; Richardson et al., 2006b). To separate the influence of these two environmental factors, the periods without any water soil stress (Sect. 2.4) are selected to analyse the temperature effect with a Q_{10} function. The regression is performed with Ts_{10} as explained above. After computing the residues of this regression on all the *R*eco values, they are used to simulate SWC impact with a Gompertz function (Janssens et al., 2003):

$$f(\mathrm{SWC}) = \exp(-\exp(a - b \cdot \mathrm{SWC})) \quad (2)$$

where a and b are two parameters. The *R*eco complete function (multiplication of the Q_{10} and Gompertz functions) is compared to the data to indicate the degree of temporal variability explained by Ts_{10} and SWC. When this procedure is applied on the DSEFR and DSIFR half-hour data, the determination coefficients (r^2) are very low (respectively 0.012 and 0.015) reflecting the fact that other factors than Ts_{10} and SWC are the major causes of the temporal *R*eco variability. The evolution of the microbial population, soil carbon content available or root and aerial biomass can be evoked but their variation rate is too low compared to the short-term measurement variation (Fig. 2). The change in footprint seems to be a more likely candidate as it could happen between two consecutives half-hours. However, this hypothesis implies a noteworthy ecosystem spatial heterogeneity and it is not apparently the case for the Hesse site that has a reasonably homogenous vegetation type and age. To give some indications about the possible impact of footprint changes on *R*eco temporal variability, we select measurements for a narrow range of Ts_{10} (from 11.5°C to 12.5°C) and excluding

soil water stress period. These measurements are compared according to their provenance from a geographical sector. This comparison cannot completely replace a full analysis combining footprint model and detailed map of soil respiration but this map is not yet available. Moreover, the subdivision in patches with homogeneous soil respiration that would result from this procedure will probably lead, in the DSEFR case, to a too low number of data per patch to investigate the temperature and soil water impact for many patches. Our *R*eco comparison between the geographical sectors shows differences. The more evident one appears when the East-Southeast sector (wind direction between 75° and 155°) is compared to the sector including the other wind directions. The ecosystem in the East-Southeast sector (mean *R*eco=6.01 μmol m^{-2} s^{-1}) produces significantly more CO_2 (p=0.034) than the ecosystem out of this zone (mean *R*eco=3.99 μmol m^{-2} s^{-1}). When sectors with 45° width are determined, the ANOVA performed on 5 groups (not enough data between 225°–360°) gives a statistically significant difference between the 5 means (p=0.029). The large *R*eco disparity found with this ANOVA (up to almost 4 μmol m^{-2} s^{-1}) has a sufficient order of magnitude to potentially explain many of the short-term *R*eco variations. One of the possible causes of this heterogeneity could be the soil respiration dependence on carbon to nitrogen content ratio (C/N). Ngao (2005) has demonstrated this dependence but it could be completely incriminated if the soil C/N map (work in progress) shows a spatial heterogeneity in agreement with the geographical sectors analysis results.

To overcome the spatial heterogeneity problem in the study of the Ts_{10} and SWC influences on *R*eco, we use the bin-average technique. The bin-averaged Q_{10} (with *T*ref=10°C) and Gompertz regressions are presented in Figs. 3 and 4. Bin-average improves clearly the goodness of fit (Table 4) with Ts_{10} being the main explaining factor for *R*eco temporal varibility, as usually found (Richardson et al., 2006b). $Reco_{10}$ (Table 4) are higher than the value for the equivalent parameter found for the soil respiration, as expected (Rs_{10} from 1.5 to 2.4 μmol m^{-2} s^{-1}, Ngao, 2005) because of the leaves and aerial wood CO_2 production. However, Rs_{10} represents 65% to 36% of the CO_2 sources according to the soil plot investigated. The percentage for the less productive

soil plots are low compared to the mean European forests value (69%, Janssens et al., 2001) but there are perhaps not representative of fluxes measured by the EC system. Contrary to $Reco_{10}$, the Q_{10} value is lower in our study (Table 4) compared to the Q_{10} estimated for soil (2.55, Ngao, 2005). This is coherent with the contribution of aerial biomass to *R*eco that includes sources less sensible to Ts_{10} than the soil.

The quality tests filtering do not lead to a substantial increase of the coefficient of determination of the regressions (for the bin-average and simple cases). Nevertheless, the fact that the regression curves for DSIFR and DSEFR give differences in *R*eco that range from 7.8% to 16.5% in the 5°C–20°C Ts_{10} interval, proves that the data eliminated by this filtering are not evenly distributed.

3.4 Gross primary productivity and net ecosystem exchange

In the two datasets, the GPP is calculated for daytime half-hours showing valid NEE measurements (46.7% for DSEFR and 91% for DSIFR). For each time step, the *R*eco simulated with the parameterisation presented in the previous section is subtracted from the NEE measurement to give GPP. The existence of two *R*eco parameter sets (DSEFR and DSIFR) leads to two GPP time series. The main factor influencing GPP is the photosynthetic photon flux density (PPFD, $\mu mol\,m^{-2}\,s^{-1}$). This influence is parameterised with the Michaelis–Menten relationship adapted by Falge et al. (2001):

$$GPP = \frac{\alpha \cdot PPFD}{1 - \frac{PPFD}{2000} + \frac{\alpha \cdot PPFD}{GPP_{2000}}} \quad (3)$$

where α is the ecosystem quantum yield ($\mu mol\,m^{-2}\,s^{-1}$) and GPP_{2000} ($\mu mol\,m^{-2}\,s^{-1}$) is the GPP for PPFD equals to 2000 $\mu mol\,m^{-2}\,s^{-1}$. The r^2 of the of the regressions of this relationship on half-hours data are 0.51 (DSEFR) and 0.56 (DSIFR), thus much higher than the *R*eco-Ts_{10} ones in the same conditions (0.012 and 0.015). The lower dispersion of the experimental points around the parameterisation curve is probably due to the lower spatial variability for GPP comparing to soil respiration (lower spatial

variability in vegetation characteristics comparing to the soil ones). To improve the GPP-PPFD relationship, the bin-average method is also implemented. This allows removing of spatial variability and possible control of other environmental factors like air temperature (Ta) or vapour pressure deficit (VPD). The influence of PPFD-GPP appears then extremely clearly (Fig. 5, Table 5). The residues of this parameterisation don't show any dependence on Ta or VPD. This is not surprising in view of the full-leaf 2005 season climate (relatively humid and temperate). Like for *R*eco, the data selection with the assessment tests do not improve the quality of the regression. This is demonstrated by the relatively low difference (<0.01) between the r^2 of the DSIFR and DSEFR regression presented in the Table 5. However, the difference between the parameters obtained with these regressions gives significant variation in GPP between DSIFR and DSEFR cases. The difference goes from 7.1% to 20.6% for PPFD going from 0 to 2050 μmol m^{-2} s^{-1}. This result suggests that the data eliminated by the filtering possess a common feature.

3.5 Total *R*eco, GPP and NEE

Total *R*eco, GPP and NEE is calculated for the 2005 full-leaf season by summing the half-hour values in the datasets gap filled with their own parameterisations presented above. The difference between the values for DSIFR and DSEFR reveals the impact of the quality tests procedure. The tests application lead to an increase from 740.4 g C m^{-2} to 816.1 g C m^{-2} for *R*eco (10.2% of variation, 75.7 g C m^{-2}). Only a minor part of this increase (8.3%, 6.3 g C m^{-2}) comes from the difference in the environmental factors of the gaps. To estimate this percentage, the gaps of the DSEFR were filled with the parameter set of DSIFR. The rest of the increase is instigated by the change of the parameter sets when the DSEFR are chosen. A similar analysis was performed for the GPP. The GPP generated by DSIFR and DSEFR are, respectively, −1306.5 and −1440.6 g C m^{-2}, therefore they let to an assimilation increase of 134.1 g C m^{-2} (10.3%). However, the impact of the environmental factors of the gaps is larger (34.9%, 46.8 g C m^{-2}). For the NEE, the quality tests induce a sequestration rise of 58.3 g

C m^{-2} (10.3%). Surprisingly, the effect of the environmental factors of the gaps is major (69.5%, 40.5 g C m^{-2}). This is explained by the fact that the GPP influence is not counterbalanced by *R*eco in opposition with the part induced by the choice of the parameter sets (DSEFR or DSIFR).

It is important to note that the impact of the quality tests on the different CO_2 fluxes have the same order of magnitude than the expected year to year variations with regards to the value already published for forests under similar climate (Aubinet et al., 2002; Carrara et al., 2003). Therefore, application of the quality tests is able to strongly influence the inter-annual analysis. For the NEE (and only for it), this conclusion is still valid even if we do not take into account the data gap filling method, considering that a variation of 40.5 g C m^{-2} are only a result from the gap characteristics.

4 Conclusion

The different tests presented in this paper are rarely applied, together and systematically, on large datasets. The results for the 2005 Hesse full-leaf season give an overview of their possible contribution. The high percentage of flagged data detected strengthens the importance to continue the work on data selection and data gap filling methods, especially during night. The strict data selection does not modify the u^* threshold that seems to be relatively constant from year to year even if the forest was heavily thinned during the winter 2004–2005.

One of the expected contributions of the quality tests was the reduction of the unexplained short-term *R*eco fluctuations. It is not really the case, because of the large *R*eco spatial heterogeneity. Even for a site with homogeneous vegetation like Hesse, the *R*eco temporal variation analysis should probably be studied from the respiration spatial heterogeneity point of view, before focusing on the data quality. In this context, the way to proceed seems to first apply a footprint model combined with a soil respiration map before to select the data and study the inter-annual variability.

Apparently, the tests have an impact on the dataset properties. On one hand, the

data elimination changes the relationship between the CO_2 fluxes and the environmental factors. On the other hand, the general features of the gaps differ when the quality tests are applied. Consequently, the gap filling by the parameterisations, using the environmental factors as independent variables, produce different *R*eco and GPP values for DSEFR and DSIFR. The total *R*eco, GPP and NEE for the 2005 full-leaf season vary all by about 10%, with more important photosynthesis exchanges, more CO_2 produced by respiration processes and a higher net sequestration when quality tests are applied. The combination of these tests have the potential ability to influence the inter-annual analysis for the CO_2 fluxes and they could perhaps give some elements to answer to the usual large discrepancy in the energy balance closure of the eddy covariance sites (Wilson et al., 2002; Kanda et al., 2004). The question of their systematic application on large databases like from the CarboEurope and FLUXNET experiments is legitimate.

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Table 1. Number of half-hours flagged by the different quality tests and fraction to the total 2005 full-leaf period (MFC corresponds to mass flow controller). The total value corresponds to the number of half-hours flagged by at least one test (not equal to the sum because of data flagged by more than one test).

Quality test	Flag	
	n	%
Anemometer anomalies	120	1.6
CO_2 IRGA anomalies	2445	33.3
MFC anomalies	5	0.1
Stationarity	1753	23.9
Footprint	107	1.5
Total	3508	47.8

Table 2. Number of half-hours flagged by the different quality tests concerning the CO_2 anomalies and fraction to the total 2005 full-leaf period. The total value corresponds to the number of half-hours flagged by at least one test (not equal to the sum because of data flagged by more than one test).

Quality test	Flag	
	n	%
Spikes	4	0.1
Mean discontinuities	142	1.9
Variance discontinuities	154	2.1
Absolute limits	6	0.1
Skewness	1063	14.5
Kurtosis	2344	31.9
Standard deviation	247	3.4
Total	2445	33.3

Table 3. Characteristics of the Q_{10} function fit applied on the DataSet Including Flagged Records (DSIFR) and DataSet Excluding Flagged Records (DSEFR) with the bin-average technique. Numbers inside parenthesis are standard errors.

Dataset	Independent variable	$Reco_{10}$ (μmol m^{-2} s^{-1})	Q_{10}	R^2
DSIFR	Ts_{10}	3.2 (0.21)	1.9 (0.26)	0.554
	Ts_5	3.4 (0.32)	1.7 (0.34)	0.297
DSEFR	Ts_{10}	3.6 (0.24)	1.8 (0.25)	0.494
	Ts_5	3.5 (0.30)	1.9 (0.35)	0.436

Table 4. Characteristics of the Q_{10} and Gompertz functions fit applied (with bin-average technique) on DataSet Including Flagged Records (DSIFR) and DataSet Excluding Flagged Records (DSEFR). The data are selected regarding to the u^* threshold. Numbers inside parenthesis are standard errors.

Function	Dataset	$Reco_{10}$ (μmol m^{-2} s^{-1})	Q_{10}	R^2
Q10	DSIFR	3.7 (0.32)	1.9 (0.31)	0.44
	DSEFR	4.2 (0.31)	1.8 (0.28)	0.447
		a	b	R^2
Gompertz	DSIFR	1.9 (3.1)	0.2 (0.17)	0.177
	DSEFR	0.9 (3.2)	0.2 (0.17)	0.125

Table 5. Characteristics of the Michaelis-Menten function fit applied (with bin-average technique) on DataSet Including Flagged Records (DSIFR) and DataSet Excluding Flagged Records (DSEFR). The data are selected regarding to the u^* threshold. Numbers inside parenthesis are standard errors.

Dataset	α	GPP_{2000}	R^2
DSIFR	−0.060 (0.0024)	−23.0 (0.29)	0.99
DSEFR	−0.072 (0.0053)	−24.7 (0.43)	0.981

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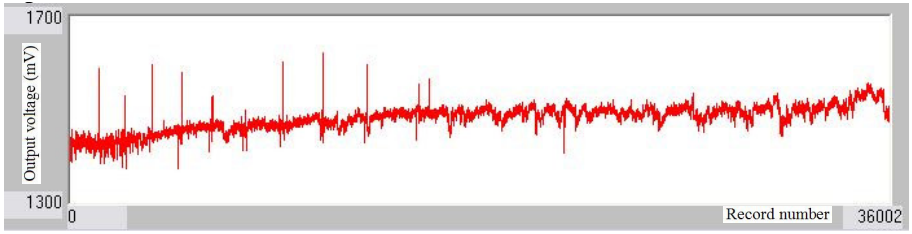

Fig. 1a. Example of high frequency records of CO_2 concentration (16 May 18:30 GMT) with instrumental anomalies.

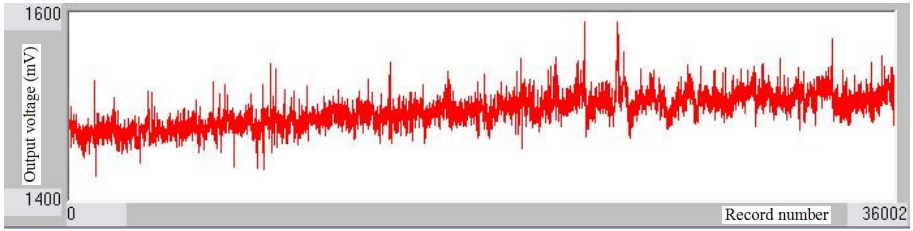

Fig. 1b. Example of high frequency record of CO_2 concentration (18 July 22:00 GMT) with intermittent turbulence.

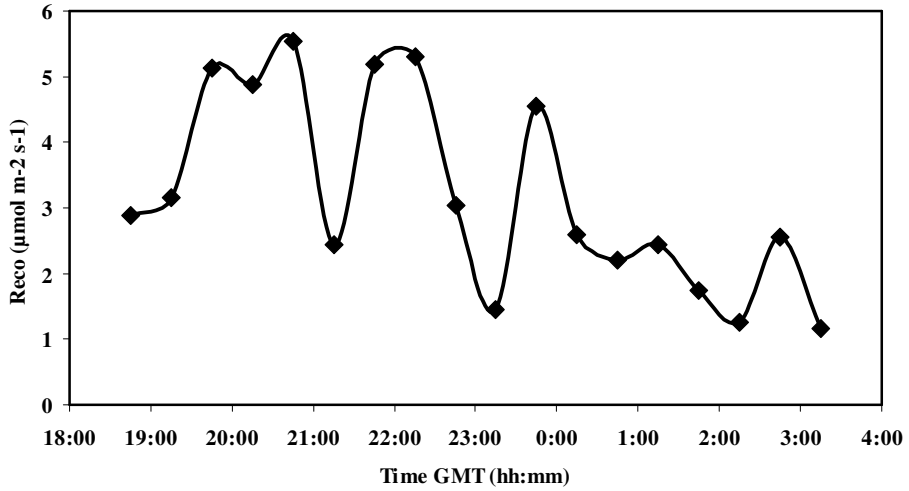

Fig. 2. Time evolution of *R*eco (with short-term fluctuations) during the night-time between the 5 and 6 August.

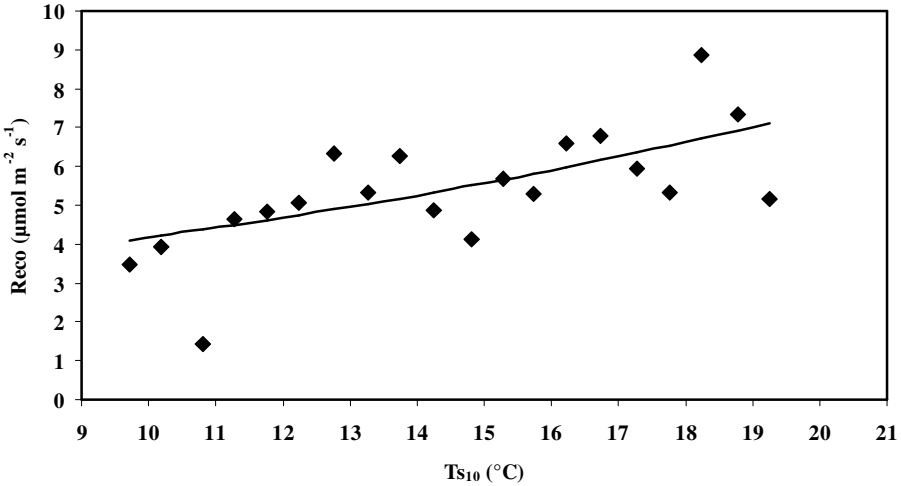

Fig. 3. *R*eco dependence on soil temperature at 10 cm depth. The dots correspond to the bin-averaged measurements for DSEFR and the line to the fit with a Q_{10} function.

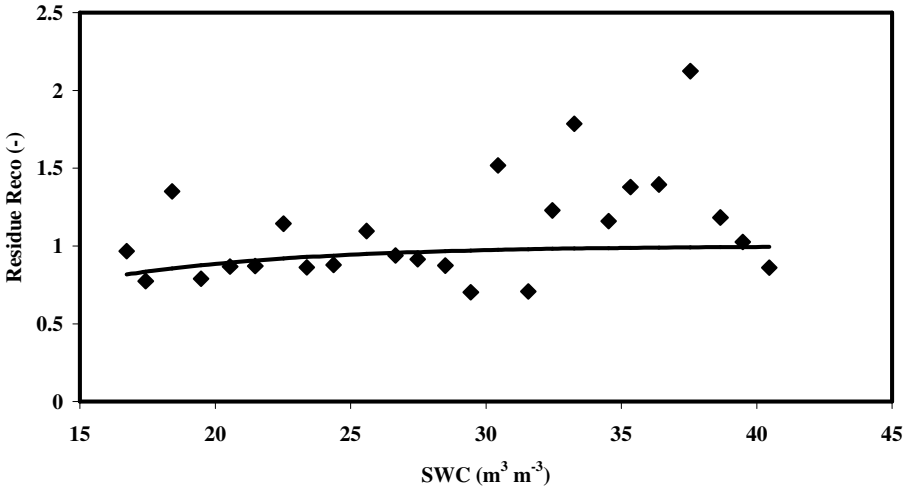

Fig. 4. Influence of the soil water content (first 10 cm depth) on the residues of the relationship between *R*eco and Ts_{10}. The dots correspond to the bin-averaged measurements for DSEFR and the line to the fit with a Gompertz function.

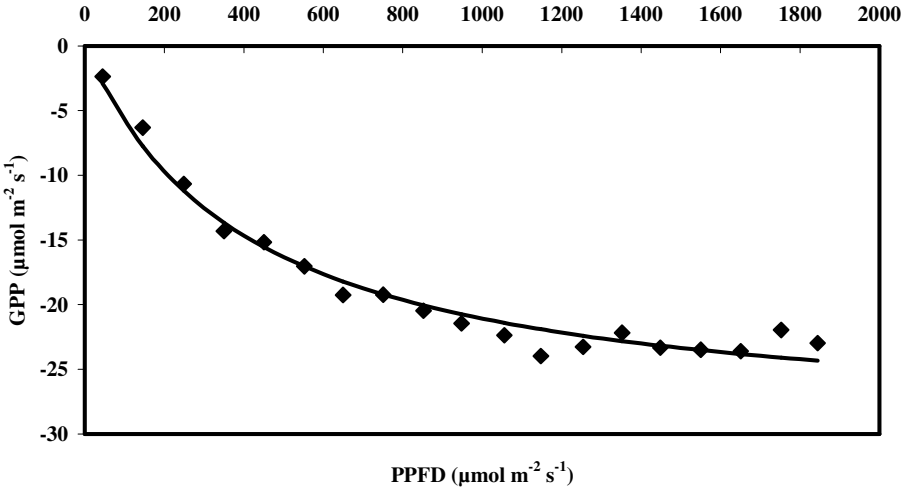

Fig. 5. GPP dependence on photosynthetic photon flux density. The dots correspond to the bin-averaged measurements for DSEFR and the line to the fit with a Michaelis-Menten function.