

Sensitivity of the annual net ecosystem exchange to the cospectral model used for high frequency loss corrections at a grazed grassland site



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ABSTRACT

Given the increasing use of the eddy covariance technique to estimate CO₂ fluxes, more attention needs to be paid to the measurement method used. Among other procedures, the way high frequency loss corrections are established and, more particularly, the choice of the cospectrum shape that is used to implement the correction appears particularly important in this regard. In this study, we compared three approaches to high frequency loss correction for CO₂ fluxes measured by a closed path eddy covariance system and evaluated their impact on the carbon balance at the Dorinne Terrestrial Observatory (DTO), an intensively grazed grassland site in Belgium. In the first approach, the computation of correction factors was based on the local cospectra, whereas the other two were based on Kansas cospectra models. The correction approaches were validated by comparing the nighttime eddy covariance CO₂ fluxes corrected with each approach and chamber-based total ecosystem respiration estimates. We found that the local cospectra differed from the Kansas cospectra shape, although the site could not be considered as difficult (i.e., fairly flat, homogeneous, low vegetation, sufficient measurement height). The Kansas cospectra have more spectral power at high frequencies than the local cospectra under (un) stable conditions. This difference greatly affected the correction factor, especially for night fluxes. Night fluxes measured by eddy covariance were found to be in good accord with total chamber based ecosystem respiration estimates when corrected with local cospectra and to be overestimated when corrected with Kansas cospectra. As the difference between correction factors was larger in stable than unstable conditions, it acts as a selective systematic error and has an important impact on annual carbon fluxes. On the basis of a 4-year average, at DTO the errors reach 71–150 g C m⁻² y⁻¹ for net ecosystem exchange (NEE), 280–562 g C m⁻² y⁻¹ for total ecosystem respiration (TER) and 209–412 g C m⁻² y⁻¹ for gross primary productivity (GPP), depending on the approach used. We finally encourage site PIs to check the cospectrum shape at their sites and, if necessary, compute frequency correction factors on the basis of local cospectra rather than on Kansas cospectra.

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1. Introduction

In the past few decades, measurements of CO₂ fluxes using the eddy covariance (EC) technique have greatly increased around the

world (Aubinet et al., 2012; Baldocchi et al., 2012; Mizoguchi et al., 2008). These data are valuable for testing and improving the land-atmosphere flux parameterizations used in climate models (Bonan et al., 2011; Chang et al., 2013; Kato et al., 2013; Melaas et al., 2013). They are also useful for upscaling exercises (Jung et al., 2011; Papale and Valentini, 2003; Tramontana et al., 2015; Xiao et al., 2012; Yang et al., 2007) and for estimating the annual net ecosystem carbon exchange (Aubinet et al., 2009; Papale et al., 2015). Robust data are needed to prevent biases in the model outputs, as well as for the estimation of the total greenhouse gas (GHG) emissions. However, the (EC) method can fail to represent accurately surface fluxes due to a physical limitation of instrumentation (Massman

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and Lee, 2002), micrometeorological limitations (Aubinet et al., 2012; chapter 5), footprint heterogeneity or the turbulent nature of the transport process (Richardson et al., 2006b). In addition to other biases, however, EC measurements are known to be affected by high frequency losses, especially when using a closed-path infrared gas analyzer (IRGA) to measure molar concentrations (Aubinet et al., 2012; Fratini et al., 2012; Ibrom et al., 2007; Mammarella et al., 2009; Runkle et al., 2012). Such losses need to be properly quantified and corrected.

Several methods dealing with high frequency losses in CO₂ measurements have been proposed in the literature. All of them involve computing the correction factor as a ratio between the integral of a reference cospectrum and the integral of the product of this cospectrum with a transfer function (Horst, 1997; Massman, 2000; Moore, 1986). A major difference between methods lies in the procedure used to compute the transfer function based either on *a priori* (theoretical or empirical) (Horst, 1997; Massman and Clement, 2004; Massman, 2000; Moncrieff et al., 1997; Moore, 1986) or *a posteriori* (experimental) methods (Aubinet et al., 2001; De Ligne et al., 2010; Fratini et al., 2012). All these methods have weaknesses and strengths and, although some progress has been made (Fratini et al., 2012), there is still some debate as to which method should be used to correct high frequency loss in EC measurements, particularly for CO₂ fluxes. Herein, the choice of the reference cospectrum used to estimate the correction factor has been investigated, using Kansas cospectra (Eugster and Senn, 1995; Horst, 1997; Mammarella et al., 2009; Massman, 2000; Moore, 1986) or local cospectra (Aubinet et al., 2001; Fratini et al., 2012) being used for this purpose. So far as we know, however, the impact of the reference cospectrum choice on the annual carbon balance has never been discussed.

This question was investigated at the Dorinne Terrestrial Observatory (DTO), an intensively grazed experimental grassland site in Belgium. The impacts of three high frequency loss correction approaches on CO₂ fluxes were compared. In the first, called the 'local approach', the local (sensible heat) cospectrum was taken as a reference cospectrum, whereas the other two, the 'Kansas approaches', used Kansas parameterization (Kaimal et al., 1972) as reference cospectra. The difference between the two latter approaches is discussed below (Section 3.3).

The approaches were evaluated by comparing the nighttime EC fluxes, corrected with each approach, with total ecosystem respiration (TER) estimates obtained from a 4-month chamber measurement campaign at the site. From this, the most realistic approach has been selected. A quantitative evaluation of the impact of the three correction approaches on the annual carbon balance at the DTO was finally made using 4 years of measurements.

2. Material and methods

2.1. Site description

The study site is grazed grassland at Dorinne, 18 km South/South-East (SSE) of Namur, Belgium (50°18'44"N; 4°58'07"E), covering an area of 4.22 ha. The vegetation of the site is homogenous in terms of the prevailing wind direction. The site is slightly sloping. It is characterized by a colluvial topography with a South-West/North-East (SW/NE) orientation and an altitude that varies from 240 m (NE) to 272 m (S) (1–2% slope). The dominant soils are colluvial regosols type, according to the FAO classification. The grassland species composition is 66% grasses (*Lolium perenne* L., *Holcus lanatus* L., *Poa trivialis* L.), 16% legumes (*Trifolium repens* L.) and 18% of other species (e.g., *Taraxacum* sp., *Ranunculus repens* L.). The mean canopy height was measured manually and varied around 0.1 m, from which we deduced the zero-plane displacement height to be of the order of 0.067 m.

A detailed micrometeorological description of the site has been given by Gourlez de la Motte et al. (2016) and Jérôme et al. (2014).

The EC system, which measured CO₂, sensible heat and water vapor fluxes, consisted of a three-dimensional sonic anemometer (CSAT3, Campbell scientific, Ltd, UK) installed on a mast at 2.62 m above the ground and a closed-path CO₂/H₂O gas analyzer IRGA (LI-7000, LI-COR Inc., Lincoln, NE, USA) maintained in a climate-controlled enclosure. Sample air was drawn from the inlet through a 6.45 m-long polyurethane tube (4 mm inner diameter) into the analyzer by a pump (NO22 AN18, KNF, Neuberger, D) at a flow rate of 11 SLPM. Two PTFE filters (Swagelok 2 μm and ACRO 50 1 μm, GELMAN, USA) were placed upstream of the inlet and the IRGA, respectively, in order to prevent any pollution of the measurement chamber. Zero and span calibrations were performed for CO₂ about once a month. Pure nitrogen (Alphagaz 1, Air Liquide, Liège, Belgium) was used for the zero and 350 μmol mol⁻¹ CO₂ nitrogen mixture (Crystal mixture, Air Liquide, Liège, Belgium) for the span. Data were recorded automatically on a data logger (CR3000, Campbell Scientific Ltd., UK) at a rate of 10 Hz and stored on a 2GB compact flash card.

2.2. Eddy covariance measurements

2.2.1. Data processing and selection

Half-hourly sensible heat and CO₂ fluxes were computed from the 10 Hz time series data, using the EDDYFLUX software (Kolle and Rebmann, 2007) and following the standard procedures defined by Aubinet et al. (2000). A stationarity test was performed after Foken and Wichura (1996). Data for which the stationarity criterion (threshold of 30%) was not satisfied for sensible heat or CO₂ fluxes and data affected by peaks (step change larger than 10 μmol mol⁻¹ for CO₂ concentration and 5 m s⁻¹ for wind speed components) were rejected from the dataset. Finally, uncorrected CO₂ fluxes lower than -2 μmol m⁻² s⁻¹ were discarded from the dataset to avoid unrealistic correction factors (Hollinger et al., 1999). Nighttime data measured under low turbulence conditions were discarded using a critical *u** threshold of 0.13 m s⁻¹ (Jérôme et al., 2014). The resulting selection was then segregated into two groups corresponding to stable and unstable stratification.

2.2.2. Correction approaches and calculation of the annual carbon balance

Three frequency correction approaches were compared. They were applied to stable and unstable datasets. During the validation phase, the fluxes corrected using each approach were compared with independent estimates, based on dynamic closed soil chamber measurements (Norman et al., 1992). For this comparison, only eddy covariance data collected during the chamber measurement campaigns were used. This fell between May and August 2015 and the set comprised 1100 half-hourly data for stable conditions and 2020 half-hourly data for unstable conditions. This comparison enabled us to determine the most realistic correction approach. In a second step, the three correction approaches were extended to the whole dataset, between 2011 and 2014, in order to estimate the impact of the selected approach on annual flux estimates. To this end, the corrected annual carbon budgets were computed following the standard procedure of daytime and nighttime data separation, *u**-filtering (Jérôme et al., 2014), flux partitioning and gap filling. Especially, the net ecosystem exchange (NEE) was gap-filled as well as decomposed into its components (gross primary productivity (GPP), and total ecosystem respiration (TER)) using the online gap filling and flux partitioning tool (Reichstein et al., 2005). In both cases, the same data selection procedure was applied.

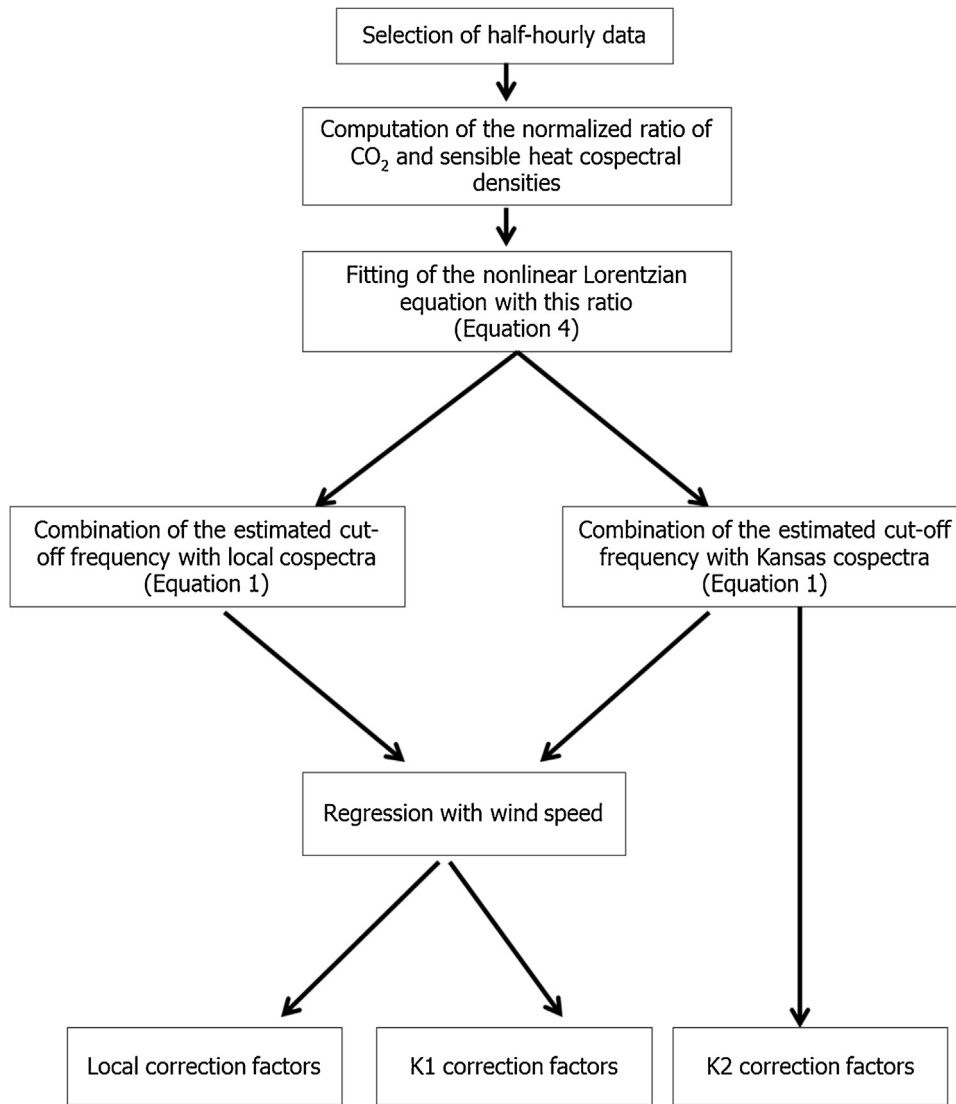


Fig. 1. Diagram of the three correction approaches developed at the Dorinne Terrestrial Observatory. 'L' is the local approach based on the sensible heat cospectrum, K1 and K2 are the Kansas approaches based on the Kansas cospectra.

2.2.3. Computation of correction factors

The general procedure followed to compute the correction factors is illustrated on Fig. 1. We computed the frequency correction factor (Φ) as (Moore, 1986):

$$\Phi = \frac{\int_0^{\infty} C_{ws}(f) df}{\int_0^{\infty} C_{ws}(f) \delta(f) df}, \quad (1)$$

where, $C_{ws}(f)$ is the 'ideal' or undamped cospectral density of the vertical wind speed (w) and the scalar dry molar fraction (s), and $\delta(f)$ is the transfer function of the EC system describing the response characteristics of the system and involving high-cut filtering effects (Aubinet et al., 2012). Implementing (Eq. (1)) therefore requires knowledge of the transfer function and undamped cospectral density.

$\delta(f)$ was deduced from the normalized ratio of CO₂ and sensible heat cospectral densities:

$$\delta(f) = N_{FT} \frac{C_{wc}(f) df}{C_{wT}(f) df}, \quad (2)$$

where N_{FT} is the normalization factor computed by assuming scalar similarity, i.e. proportionality of undamped CO₂ and sensi-

ble heat cospectra. Consequently, N_{FT} was computed as described in Aubinet et al. (2000):

$$N_{FT} = \frac{\int_{f_1}^{f_2} C_{wT}(f) df}{\int_{f_1}^{f_2} C_{wc}(f) df} \quad (3)$$

where, f_1 and f_2 are limit frequencies, chosen arbitrary to be low enough for the attenuation be negligible but high enough for the number of points used to estimate the integrals to be sufficient and the uncertainty on the normalization factors to be low (Aubinet et al., 2000).

For each half-hour, these densities were calculated using the EDDYSPEC software (Kolle and Rebmann, 2007) and following the procedure described by Foken et al. (2012b) and De Ligne et al. (2010). A nonlinear Lorentzian equation (Eugster and Senn, 1995) was then fitted on their ratio:

$$\delta(f) = \frac{1}{1 + \left(\frac{f}{f_{co}}\right)^2} \quad (4)$$

where, f represents the natural frequency and f_{co} the cut-off frequency of the system for the CO₂. Cut-off frequency (f_{co}) was deduced from the fitting as well as its 95% confidence interval ($\sigma_{f_{co}}$).

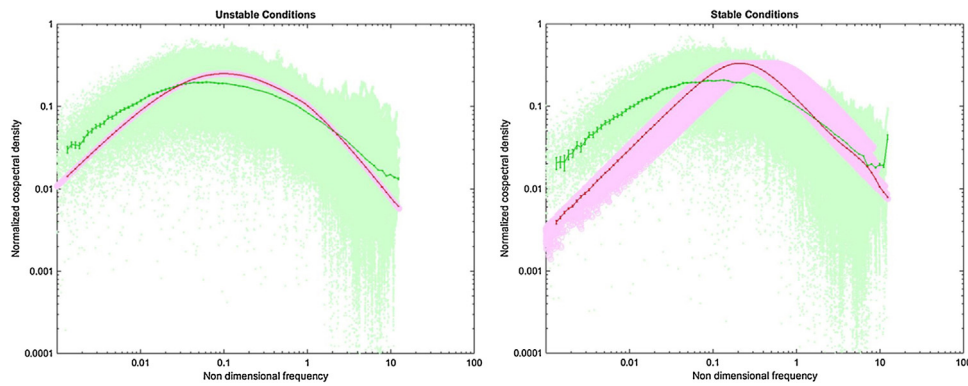


Fig. 2. Ensemble of normalized Kansas (red dots) and local (sensible heat) cospectra (green dots) during unstable (left) and stable (right) conditions in log-log space. The red and green lines represent their respective averages.

Only half-hourly data for which ($\sigma_{f_{co}}$) were lower than 0.1 Hz were retained for further analysis. This corresponded approximately to 55% of the initial dataset. From this dataset, the modal value in the f_{co} distribution was calculated and kept for the remaining analysis. The same transfer function was used in all approaches.

Undamped cospectral densities could be computed in two ways: local (L) and Kansas (K) approaches. Fundamental to the three approaches is the assumption of cospectral similarity of scalars in the atmospheric boundary layer (Aubinet et al., 2012; Fratini et al., 2012; Massman and Clement, 2004).

In the local approach, the local (sensible heat) cospectrum was chosen as the undamped cospectrum. The approximation is reasonable because the sensible heat measurements are largely unaffected by cospectral attenuation (cut-off frequency: 0.37 ± 0.05 Hz). The computation was made as above, using a fast Fourier transform algorithm implemented with EDDYSPEC software (Kolle and Rebmann, 2007) on segments of 4096 data points.

In the Kansas approach, undamped cospectral densities were estimated using the Kansas cospectra models for sensible heat described by Kaimal et al. (1972):

$$\frac{fC_{wT}(f)}{w'T'} = \begin{cases} \frac{11n}{(1 + 13.3n)^{7/4}} & \text{for } n \leq 1 \\ \frac{4n}{(1 + 3.8n)^{7/3}} & \text{for } n \geq 1 \end{cases} \quad (5)$$

in unstable conditions and,

$$\frac{fC_{wT}(f)}{w'T'} = \begin{cases} \frac{0.81(n/n_0)}{1 + 1.5(n/n_0)^{2.1}} & \end{cases} \quad (6)$$

with $n_0 = 0.23(1 + 6.4\zeta)^{3/4}$ in stable conditions. In Eqs. (5) and (6), n is a dimensionless frequency defined as: $n = f(z_m - d)/\bar{u}$; d (m) is the zero plane displacement height; z_m (m) is the measurement height; \bar{u} ($m\ s^{-1}$) is the wind speed; $\zeta = (z_m - d)/L_{MO}$ is the stability parameter; L_{MO} (m) is the Monin Obukhov length and $w'T'$ is the measured covariance of the vertical wind speed and the air temperature.

The correction factor was then computed every half-hour by combining in Eq. (1) the transfer function and the reference cospectrum computed every half-hour. Depending on the approach, local or Kansas cospectra were used.

In the local approach (L) and in the first Kansas approach (K1), a regression was fitted on the relation between half-hourly correction factors and wind speed, separately for stable and unstable conditions. A linear regression was chosen, according to (Aubinet et al., 2001 or Fratini et al., 2012) (see Section 3.1, Fig. 4). Non linearities in this response, as predicted by Massman and Clement (2004) and Wohlfahrt et al. (2005) were not taken into account here as they

mainly result from a sensor separation effect, which, in the present case, is small compared to the tube attenuation effect. The effective correction factor was then estimated every half-hour using this regression and wind speed data. In the second Kansas approach (K2), a correction factor was directly applied to the half-hourly data. The difference between the first and the second Kansas approaches was then in their computation procedure. This allowed comparing more easily the local approach and the first Kansas approach; both followed indeed the same procedure for the computation of the correction factors.

2.3. Chamber-based TER estimates

2.3.1. Soil/grass efflux measurements

Eighteen CO₂ efflux measurement campaigns were held between May and August 2015. The measurements were taken between 10 am and 6 pm in four sectors that had been delimited around the EC tower. Three of them were situated SSW of the tower and the fourth was NE of the tower. These are the two dominant wind directions at the site. Some 28 soil collars, 15.5 cm high and 10 cm in diameter, were inserted into the soil (including the present grass) at least 3 days before the chamber soil/grass respiration measurements.

The measurements were taken manually with an EGM-4 IRGA analyzer (PP Systems, Haverhill, MA) connected to an SRC-1 chamber (PP Systems, Haverhill, MA). In total, 450 independent measurements were made. For each measurement there were three repetitions and the CO₂ concentration in the soil chamber was recorded every 4.8 s. One single measurement lasted for 120 s if the maximum change, fixed at 50 ppm, allowed in CO₂ concentration was not reached. It was automatically stopped when the maximum was reached. Finally, soil temperature (H-I 145 T-Shaped Thermometer, HANNA instruments, USA) at a depth of 5 cm and soil moisture (Theta probe ML2X, Delta-T Devices, UK) at a depth of 0–5 cm were measured manually near the soil collars.

The soil/grass respiration R_S ($\mu\text{mol m}^{-2} \text{s}^{-1}$) was calculated based on the increase in CO₂ in the chamber over time (Eq. (7)) (Suleau et al., 2011), according to:

$$R_S = \frac{P_{atm} \times V}{R \times T_s \times S} \times \frac{dc}{dt} \quad (7)$$

where, $R = 8.314 \text{ J K}^{-1} \text{ mol}^{-1}$ is the gas constant; P_{atm} (Pa) is the atmospheric pressure; V (m^3) is the chamber volume; S (m^2) is the soil surface area intercepted by the collar; T_s (K) is the soil temperature; and dc/dt ($\mu\text{mol mol}^{-1} \text{s}^{-1}$) is the rate of CO₂ concentration increase within the chamber.

A quality criterion was applied to the data, with measurements being discarded if the quality of the linear regression was not suf-

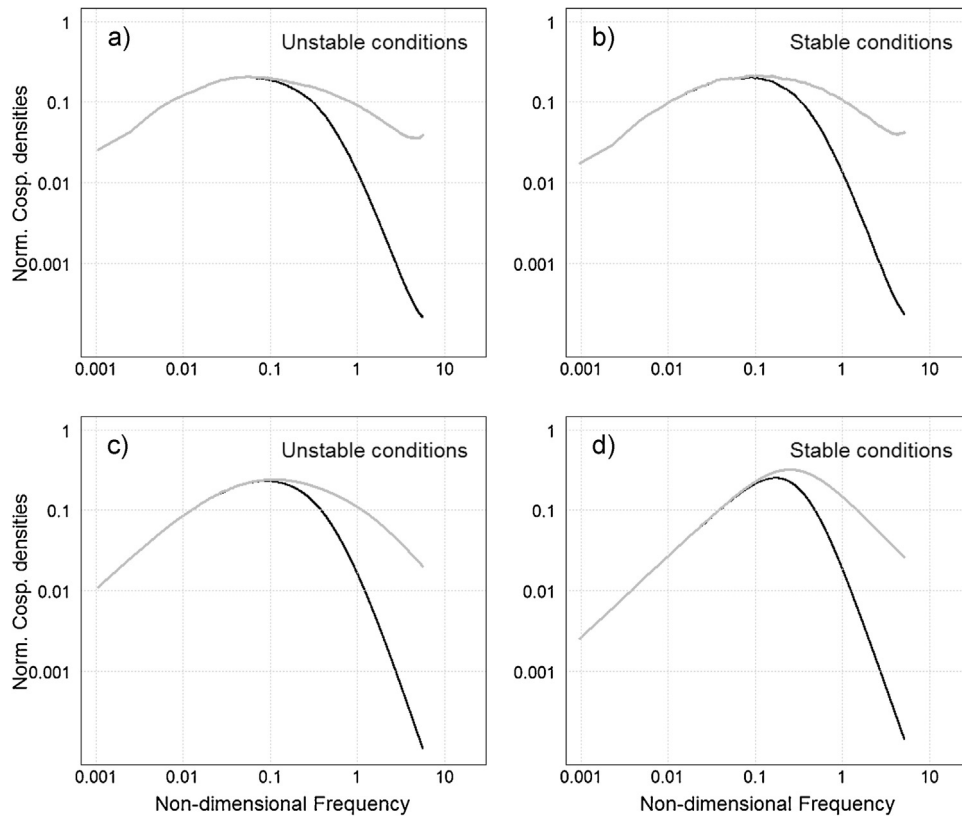


Fig. 3. Undamped (grey color) and damped (black color) cospectra, considering a Lorentzian transfer functions with a cut-off frequency modal value of 0.37 Hz; a) and b) local cospectra; c) and d): Kansas cospectra; for unstable (a and c) and stable (b and d) conditions.

ficient ($R^2 < 0.90$). Afterwards, they were averaged per soil collar to capture the variability between repetitions and thus their associated uncertainties.

2.3.2. Cattle respiration estimate

As the pasture is grazed, total ecosystem respiration (TER) also includes cattle respiration, which is captured by EC measurements but not by soil/grass chambers. Total chamber based TER estimates (R_{ST}) were thus obtained by summing *in situ* soil/grass respiration and an estimate of cattle respiration based on the analysis performed by Jérôme et al. (2014) at the same site. They estimated the average emission per livestock unit as $2.59 \text{ kg C LU}^{-1} \text{ day}^{-1}$. On this basis, as during our measurement campaigns the average stocking rate reached 4 LU ha^{-1} , we computed the averaged cattle respiration as $1.02 \text{ } \mu\text{mol m}^{-2} \text{ s}^{-1}$. It is worth noting, that cattle respiration probably varied during the measurement campaigns because it would also have depended on cattle repartition in the footprint and on daily stocking rate changes. The impact of these variations is however limited as, in average, cattle respiration corresponds to about 12% of soil/grass respiration.

2.4. Validation of the correction

The three high frequency loss correction approaches were evaluated by comparing the corrected nighttime CO_2 fluxes (R_{SL} , R_{SK1} and R_{SK2}) and the chamber-based TER estimates (R_S).

Nighttime hours were defined as periods when global radiation was lower than 10 W m^{-2} . Eddy fluxes were computed half-hourly as the sum of the turbulent flux measured by the EC system and of the storage term (Foken et al., 2012a). In order to avoid the biases (e.g. the decrease of soil/grass respiration when anaerobic condi-

tions prevail and depress aerobic microbial activity) that can occur when soil is saturated by water (Knowles et al., 2015; Luo and Zhou, 2006), data corresponding to soil water content at a depth of 5 cm that were higher than 30% were discarded from both nighttime EC and *in situ* soil CO_2 efflux measurements. These represented 15% and 2% of *in situ* soil CO_2 efflux measurements and nighttime eddy covariance data respectively.

In order to get rid of the temperature dependence of TER, both corrected nighttime EC fluxes (R_{SL} , R_{SK1} and R_{SK2} , $n_{\text{data}} = 493$) and total chamber based respiration measurements (R_{ST} , $n_{\text{data}} = 381$) were first binned into soil temperature classes containing 40 elements each. However, as these estimates were not obtained during similar temperature conditions, the comparison could be made only on the overlapping temperature ranges. To this aim, a second data sorting was made, constituting two classes of variable sizes covering the temperature ranges $16 \pm 2 \text{ }^\circ\text{C}$ and $20 \pm 2 \text{ }^\circ\text{C}$. Flux averages (m_i) and standard errors (ε_i) were calculated for each class. The normalized difference (u_{obs}) between the averaged chamber-based TER and averaged nighttime EC fluxes corrected by each approach was calculated for both temperature classes following:

$$u_{\text{obs}} = \frac{m_1 - m_2}{\sqrt{\varepsilon_1^2 + \varepsilon_2^2}} \quad (8)$$

The difference between the two estimates was considered as significant at $\alpha = 0.05$ if $u_{\text{obs}} > 1.96$ (Dagnelie, 2011). The most realistic approach to high frequency loss correction was selected from this comparison.

The statistical tests, models and figures were made using R software (R version 3.1.2) and Matlab R2014b (Mathworks, Inc., USA) for numerical cospectral analyses.

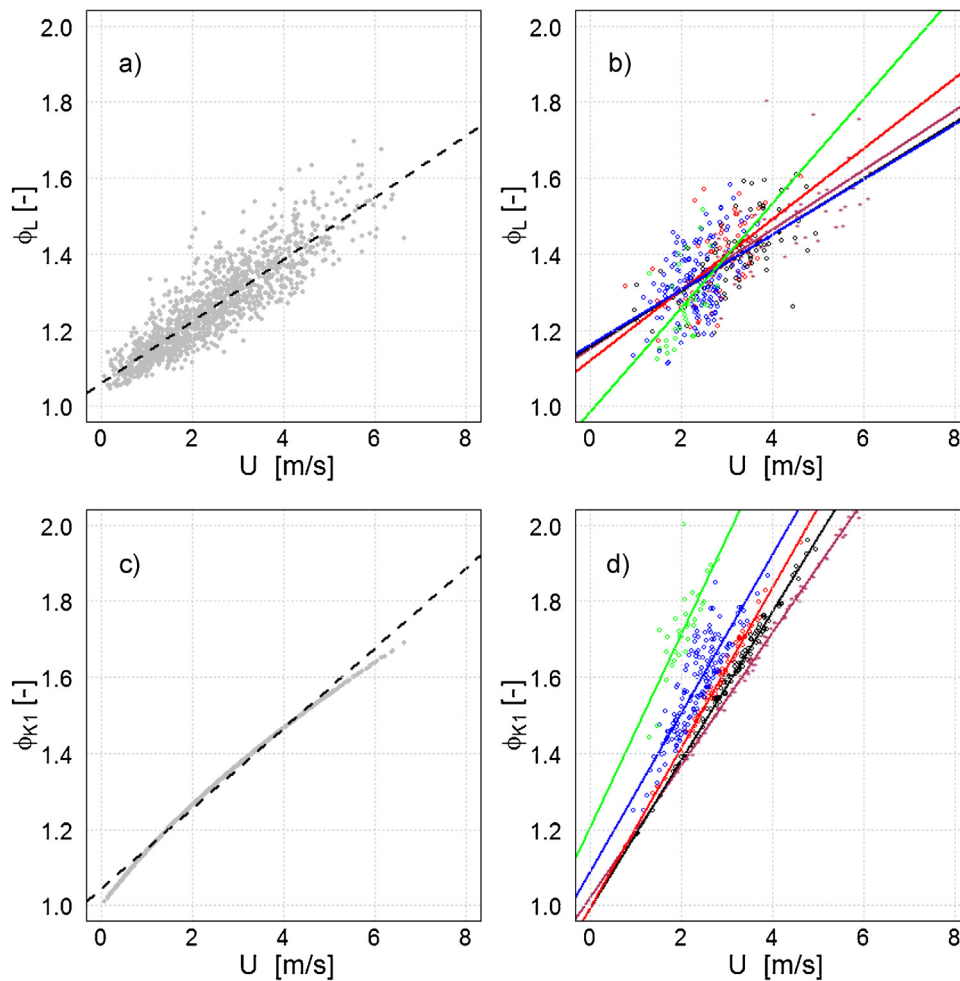


Fig. 4. Cospectral correction factors for the local and Kansas approaches as a function of wind speed, during unstable conditions (a, c) and for different stable stratifications (b, d) obtained with the cut-off frequency of 0.37 Hz during the investigated period. Black dotted line ($\zeta < 0$) and, maroon ($0 < \zeta < 0.02$), black ($0.02 \leq \zeta < 0.04$), red ($0.04 \leq \zeta < 0.06$), blue ($0.06 \leq \zeta < 0.2$) and green ($\zeta \geq 0.2$) solid lines, represent the linear regressions. The numerical values of the regression parameters and their 95% confidence intervals are given in Table 1.

3. Results and discussion

3.1. Cospectral analyses and correction factors

Fig. 2 presents the normalized local and Kansas cospectra (Eqs. (5)–(6)) and their averages on the selected half-hourly dataset, separately for stable and unstable conditions. In stable conditions, the local cospectrum reached a $-4/3$ slope in the inertial range, as expected, but in unstable conditions the Kansas cospectrum have more spectral power than the local one. At lower frequencies, the differences were more apparent: in both stable and unstable conditions, the Kansas cospectrum was larger than the local cospectrum between 0.1 and 1 Hz and smaller than local cospectrum at lower frequencies ($n < 0.1$ Hz).

These differences in shape clearly affect correction factors, those calculated using the local cospectrum (Φ_L) being systematically lower than those calculated with the Kansas cospectra (Φ_{K1} , Φ_{K2}). By considering a transfer function for both atmospheric stability conditions with the estimated modal value of the cut-off frequency (0.37 Hz) (Fig. 3), the deviation reached 9% in average between Φ_{K1} and Φ_L and 16% in average between Φ_{K2} and Φ_L .

In all cases, there was a clear increase in the correction factors with increasing wind speed (Fig. 4), as predicted by theory (Aubinet et al., 2012). The estimated regression parameters, however, were found to be much higher for the first Kansas approach than for

the local approach (Table 1). The difference was particularly large during stable conditions, where the regression slopes differed by a factor greater than two (Figs. 4b, d). It was smaller during unstable conditions (Figs. 4a, c), but nevertheless reached 37% (Table 1).

3.2. Evaluation of the correction procedure

The evolutions with temperature of the different estimates of total ecosystem respiration are presented in (Fig. 5).

As expected, the temperature ranges did not coincide exactly, due to the difference between nighttime and daytime temperatures. Over the 18 measurement campaigns, the soil temperature at a depth of 5 cm varied between 16 and 27 °C in the day and between 9 and 22 °C at night. Fig. 5 suggests however that, in the common temperature range, the average total chamber-based TER (R_{ST}) was closer to the eddy fluxes corrected using the local approach (R_{SL}) than to the others.

In order to make the comparison more substantial, the different TER estimates were gathered in two classes covering the temperature ranges 16 ± 2 °C and 20 ± 2 °C, respectively, and their averages were compared. Results are given in Table 2. It appears first that, in both temperature classes, the normalized differences (u_{obs}) between chamber-based and eddy covariance TER estimates are all positive, suggesting that eddy covariance estimates are always larger than chamber-based estimates. However, these dif-

Table 1
Slopes, intercepts and their 95% confidence intervals of the linear regression obtained between the correction factors and wind speed during the investigated period (from May to August 2015), separately for unstable and different stable conditions and for the first Kansas (K1) and the local (L) approaches. ndata represents the number of the half-hourly data that was used in the linear regression for each stability condition.

Stability ranges	Local approach		Kansas 1 approach		ndata
	Slope	Intercept	Slope	Intercept	
$\zeta < 0$	0.08 ± 0.006	1.044 ± 0.0024	0.11 ± 0.001	1.06 ± 0.0005	1251
$0 < \zeta < 0.02$	0.08 ± 0.065	1.151 ± 0.016	0.17 ± 0.010	1.021 ± 0.002	73
$0.02 \leq \zeta < 0.04$	0.07 ± 0.056	1.158 ± 0.017	0.20 ± 0.011	0.992 ± 0.003	92
$0.04 \leq \zeta < 0.06$	0.09 ± 0.089	1.12 ± 0.031	0.21 ± 0.015	0.99 ± 0.005	61
$0.06 \leq \zeta < 0.2$	0.07 ± 0.063	1.162 ± 0.026	0.21 ± 0.043	1.089 ± 0.018	150
$\zeta \geq 0.2$	0.14 ± 0.194	0.984 ± 0.093	0.25 ± 0.155	1.206 ± 0.074	31

Table 2
Results of the comparison at similar temperature between total chamber-based (R_{ST}) and eddy covariance TER estimates corrected with different approaches (R_{SL} , R_{SK1} and R_{SK2}). ndata represents the number of data in each class. p represents the probability level.

	Temperature class	R_{ST}	R_{SL}	R_{SK1}	R_{SK2}
Mean \pm sterr (ndata)	16	8.12 ± 0.35 (59)	8.50 ± 0.17 (144)	9.55 ± 0.19 (144)	10.67 ± 0.21 (144)
	20	9.39 ± 0.16 (202)	9.96 ± 0.31 (89)	11.44 ± 0.40 (89)	12.77 ± 0.47 (89)
Difference			$R_{SL} - R_{ST}$	$R_{SK1} - R_{ST}$	$R_{SK2} - R_{ST}$
	16		0.38	1.43	2.55
	20		0.57	2.04	3.38
u_{obs}	16		0.96 ($p = 0.33$)	3.55 ($p < 0.001$)	6.19 ($p < 0.001$)
	20		1.62 ($p = 0.055$)	4.76 ($p < 0.001$)	6.81 ($p < 0.001$)

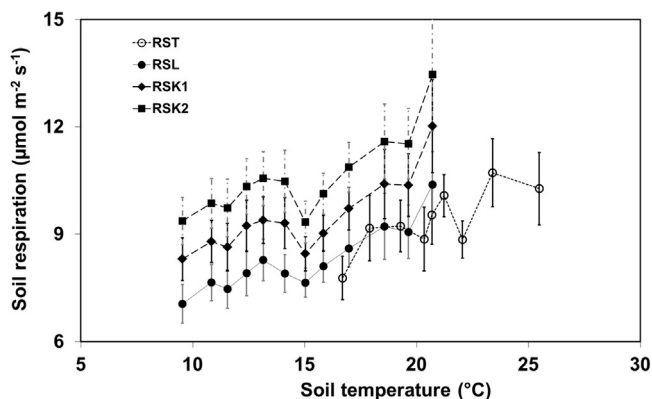


Fig. 5. Relationship between total ecosystem respiration and soil temperature for the corrected eddy covariance data (closed symbols) and for chamber-based TER estimates (open symbols): R_{SL} (black circles) R_{SK1} (black diamonds) and R_{SK2} (black squares). Each point on the graph is an average of 40 measurements. The errors bars represent the 95% confidence intervals. Only complete data classes are represented in the figure.

ferences are not significant ($p > 0.05$) for fluxes computed with the local approach while they are highly significant ($p < 0.001$) for the fluxes computed with the Kansas 1 and Kansas 2 approaches. This suggested clearly that both Kansas approaches provided significantly higher estimates than the total ecosystem respiration while the local approach gave more compatible estimates. Some uncertainties still affect the comparison procedure, however. First cattle respiration was estimated as an average. This does not take changes in daily stocking rate and in cattle position in the footprint. As a result, an uncertainty remains on this term. Another issue is the choice of the reference temperature that was used to sort respiration data, which could have influenced the comparison between eddy covariance and chamber-based TER estimates. In the present

study we chose soil temperature at 5 cm, which appears reasonable as soil contributes largely to TER. Air temperature would have been a good alternative too and this choice would have slightly increased the difference between chamber-based and eddy covariance TER estimates. Indeed, chamber fluxes were collected during the day when air temperatures were higher than soil temperature while eddy covariance fluxes were taken from nocturnal periods when air temperatures were lower than soil temperatures. This would have induced in (Fig. 5) a shift to the right of chamber-based estimates and a shift to the left of the eddy covariance estimates. This would have increased again the mismatch between Kansas and chamber-based estimates but also resulted in a less good agreement between local and chamber-based estimates. Clearly, more extensive chamber campaigns, including both night and day measurements, would be necessary to refine this comparison.

3.3. Impact of the reference cospectrum choice and correction approach on CO_2 fluxes

3.3.1. Half-hourly fluxes

The analysis was extended to the daytime EC data and the deviation between the local and Kansas approaches was quantified by comparing corrected CO_2 fluxes with the local approach and both Kansas approaches. The differences were estimated to be 14 and 28% for the nighttime CO_2 fluxes (Figs. 6a, b) and 4 and 9% for the daytime CO_2 fluxes (Figs. 6c, d). The fact that these differences were larger at night than during the day suggests that the error resulting from an incorrect correction might have acted as a 'selective systematic' error (Moncrieff et al., 1996; Rannik et al., 2004), as in the case of the u^* -filtering correction (Moncrieff et al., 1996; Aubinet et al., 2001). Therefore, because the error had a greater impact on the positive fluxes than on the negative fluxes, it would be expected to result in important biases in annual sums.

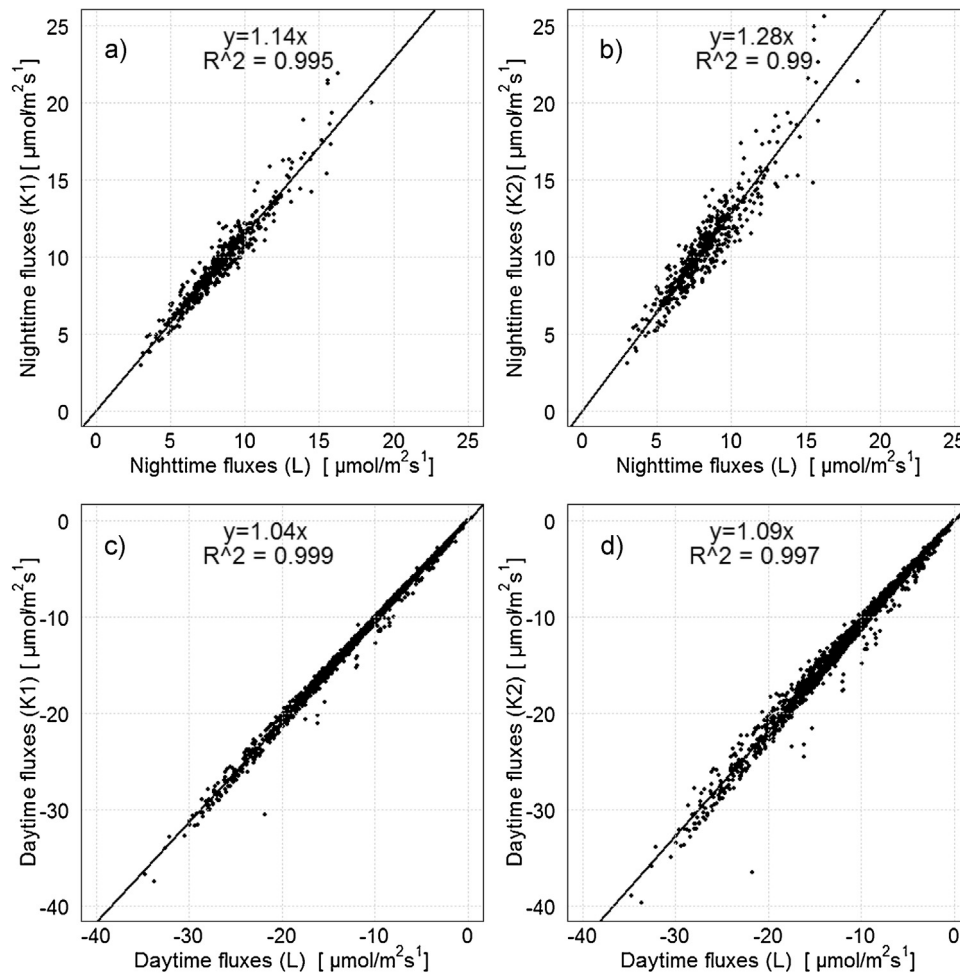


Fig. 6. Correlation between the CO_2 fluxes corrected by the Kansas and local approaches during (a, b) nighttime and (c, d) daytime; a and c first Kansas approach; b and d second Kansas approach during the investigated period: May to August 2015.

3.3.2. Annual sums

The preceding analysis clearly showed that the choice of the cospectral correction approach was critical at the DTO. In order to evaluate the impact of such choice on the annual fluxes, the correction procedures were extended to the 2011–2014 dataset. Over these 4 years, the average flux difference between L and K1 or L and K2 amounted to 412 and 209 $\text{g C m}^{-2} \text{y}^{-1}$ for GPP (Fig. 7a), 562 and 280 $\text{g C m}^{-2} \text{y}^{-1}$ for TER (Fig. 7b), and 150 and 71 $\text{g C m}^{-2} \text{y}^{-1}$ for NEE (Fig. 7c). The relative differences ranged from 9 to 19% (GPP) and 14 to 27% (TER) between L and K1 and between L and K2, respectively. This shows that the choice of reference cospectrum could significantly affect all fluxes (GPP, TER) and, in this case, change the site from being a net C sink to being a weak net C source. The fact that the approaches based on the Kansas cospectral corrections gave the highest estimates of all annual fluxes could be attributed to the site-specific cospectral shape obtained, whatever the atmospheric stability conditions, because the Kansas correction factors were always larger than those computed with the local cospectra.

3.4. Shape of the cospectrum

The main reason for these differences was that the local cospectrum differed from the cospectrum shape proposed by Kaimal et al. (1972). Let's remark that these differences appear although both site choice and tower design were made taking the standard requirements (Munger et al., 2012) into account. The site is almost flat (a relative slope of 1–2% in the NE direction) and has

homogeneous vegetation in terms of prevailing wind direction. The measurement height is 2.62 m, much higher than the vegetation canopy, which rarely exceeds 30 cm in height. Although there are a few sparse trees in the footprint area, they are far away and we considered them unlikely to have created a flow distortion that would have explained the observed differences, particularly in the inertial subrange. The presence of a valley in the North-West direction is expected to be of small importance because it corresponds to infrequent wind occurrences. This suggests that cospectra differing from Kansas shape can be met even at sites that meet recommended quality criteria.

Previous literature provides some examples not only above complex sites (Massman and Clement, 2004; Sakai et al., 2001; Su et al., 2004), where measurements were made in the roughness sublayer in which turbulent flow is known to be affected by the size of roughness elements (Kaimal and Finnigan, 1994) but also at a flat land site (Smedman et al., 2007), at a pasture and a flat paddocks sites (Laubach and McNaughton, 2009) and over a smooth playa (McNaughton et al., 2007). By investigating how these cospectral models fitted *in situ* data at two forested sites, Su et al. (2004) found that their Kansas cospectra differed from those of sensible heat in both stability conditions, and in particular were more sharply peaked in the inertial subrange. During neutral atmospheric conditions and above a flat terrain and a rocky mountain site, Massman and Clement (2004) reported similar results as those obtained by Su et al. (2004). Smedman et al. (2007) however, argued that these differences were determined by the dynamics of the whole boundary

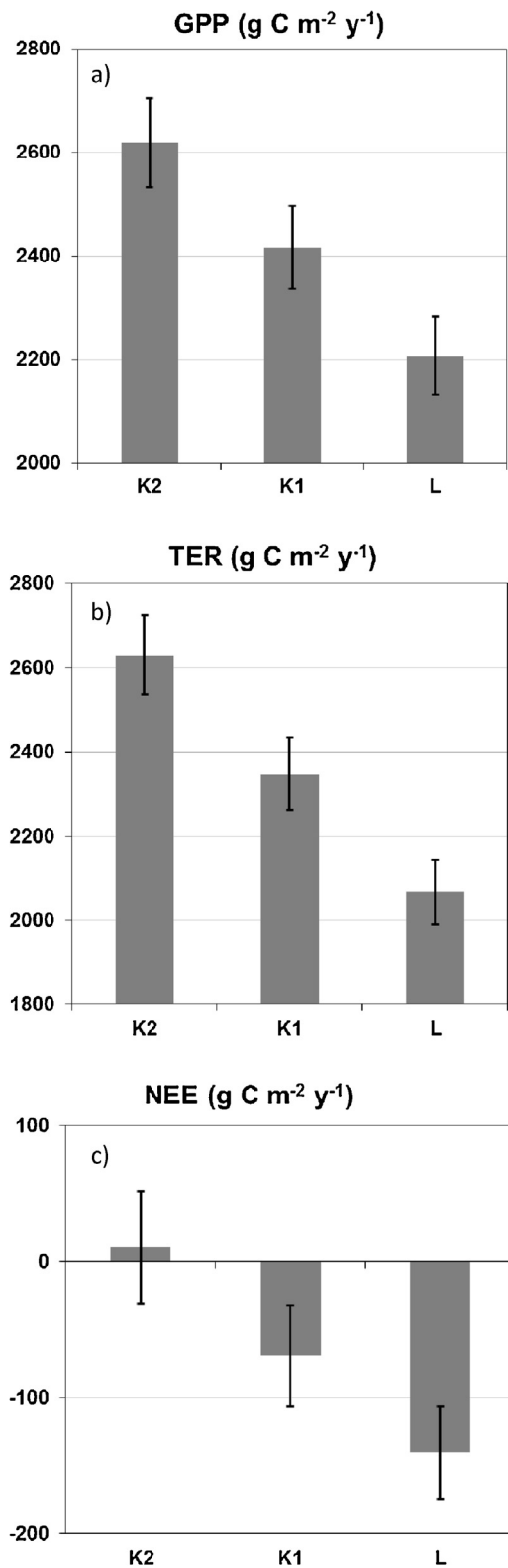


Fig. 7. The 4-year (2011–2014) average and their standard errors of the annual estimates of (a) gross primary productivity (GPP, g C m⁻² y⁻¹), (b) total ecosystem respiration (TER, g C m⁻² y⁻¹) and (c) net ecosystem exchange (NEE, g C m⁻² y⁻¹) corrected with the local (L), first (K1) and second (K2) Kansas approaches, respectively, at the Dorinne Terrestrial Observatory (DTO).

layer rather than being simply dependent on the surface boundary conditions. An alternative parameterization of the heat cospectral density have also been proposed by Wohlfahrt et al. (2005) and Massman and Clement (2004). In view of the numerous differences reported between local cospectrum and Kansas cospectra, even at sites that could not be considered as difficult (in the sense of Finnigan, 2008), it can be expected that other sites will experience similar problems. Given the impact of the cospectrum shape on both high frequency correction and annual carbon balance, we therefore recommend that site PIs systematically check the cospectrum shape at their sites and, if necessary, compute frequency correction factors on the basis of local cospectra rather than on Kansas cospectra. Finally, the corrected fluxes should be validated when possible.

4. Conclusion

In this study, we compared three approaches to high frequency loss correction; all based on the Monin-Obukhov similarity, and evaluated their impact on the annual carbon balance at the Dorinne Terrestrial Observatory, an intensively grazed grassland site in Belgium. The CO₂ fluxes were measured using a closed-path eddy covariance system. The results showed that the correction factor based on the local cospectra was more appropriate and gave more realistic estimates of nighttime CO₂ fluxes when compared with total chamber-based TER estimates than the correction factors computed with Kansas cospectra. This is because the shapes of sensible heat cospectra at the DTO were found to differ from the Kansas shapes, having less spectral power at high frequency than the Kansas cospectra. This led to an overestimation of the cospectral correction factor, which averaged over 4 months, of 4–9% in the daytime and 14–28% in the nighttime CO₂ fluxes, depending on the approach. The impact on annual sums is huge. Especially, at the DTO, the choice of Kansas rather than local cospectra reversed the annual carbon balance from being a net C sink to being a weak C source.

As the DTO is not a complex site, we suspect that many sites could be affected by a similar problem and we thus strongly advocate site PIs to apply the spectral correction on the basis of locally established cospectra rather than on Kansas cospectra. Although challenging, a comparison between eddy covariance and chamber-based TER estimates could help validating the correction procedure.

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