Sampling and interpolation strategies derived from the analysis of continuous soil CO_2 flux

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Abstract

Soil CO_2 flux (F_s) can be measured either manually or automatically. While manual measurements are well suited to capture the spatial variability of F_s, automated measurements are able to capture its temporal variability at fine time scales. The manual method is the most commonly used method to estimate annual carbon budgets. However, such estimates can be biased depending on the measurement frequency, the time at which measurements are made, and the method used to interpolate F_s between two measurements. In this study, we investigated the effects of within-day measurement frequency and of the time of measurement on the estimation of daily F_s. We also investigated the effects on cumulative F_s estimates of weekly and fortnightly sampling frequencies over several months and of the interpolation method used to cumulate F_s. We based our analyses on two complete datasets of automated measurements (one 12-month and one 4-month) recorded in two contrasting ecosystems (a tropical eucalypt plantation and a temperate poplar plantation). Low-frequency time step within a day (every 360 min for the eucalypt and every 180 min for the poplar plantations) was sufficient to capture mean daily F_s accurately. Furthermore, in the tropical site, measurements averaged over any 6h period provided good estimates of the daily flux. By contrast, biases were observed in the temperate site. With one measurement per week, linear interpolation methods provided accurate cumulative fluxes at both sites. However, all interpolation methods failed to produce robust estimates of cumulative F_s in the temperate plantation with one measurement every two weeks. Automated measurements will help to select the best time slot for manual measurements or to correct manual measurements from the apparent deviation between measurements collected during the sampling period and the 24 h-mean CO_2 flux. It will also be useful to elaborate empirical equations used to cumulate F_s obtained manually. Combining manual and automated methods will enhance the accuracy of annual soil carbon budgets in forest plantations.

Key words: soil respiration / carbon cycle / automated system / temporal variability

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1 Introduction

Soil CO_2 flux (F_s) is the largest component of terrestrial ecosystem carbon (C) budgets after photosynthesis and represents a large fraction of ecosystem respiration (*Granier* et al., 2000). The quantification of this important flux is still highly uncertain and there is a need to constrain these uncertainties for a better understanding of the C cycle at both the ecosystem and global scales (*Vargas* et al., 2011). F_s and the soil temperature (T_s) are usually exponentially related and their relationship is affected by the soil water content (*SWC*) (*Xu* and *Qi*, 2001; *Jassal* et al., 2008). Photosynthesis, phenology, and root dynamics also play a role in modulating seasonal F_s (*Curiel Yuste* et al., 2004; *Baldocchi* et al., 2006; *DeForest* et al., 2006; *Bahn* et al., 2010; *Vargas* et al., 2010).

Two approaches are commonly used to measure F_s. For the 'manual' method, a fixed collar is set into the top layer of the soil to hold a portable chamber, which, once installed, is connected to an infra-red gas analyzer (IRGA). The number of collars at a site can be relatively high, thus, making it possible to cover a large spatial variability. Since this method is time-consuming, measurements cannot be repeated extensively and the time between measurements is thus typically more than a week. By contrast, with several measurements of F_s per day, the automated method provides a detailed description of the temporal variability in F_s. However, technical constraints associated with sharing the gas analyzer (length of the tubing connecting IRGA to all the chambers) limit the spatial distribution of chambers (*Rochette* and *Hutchinson*, 2005). In most studies, the manual approach is still used to

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determine cumulative soil CO_2 flux (F_{sc}) over several months or years and integrate spatial variability. It is often hypothesized that F_s measurements taken over a short time period within a day, at intervals of several days, are representative of the mean daily flux (*e.g.*, *Epron* et al., 2004; *Ryan* et al., 2010). But this assumption is often violated since F_s may vary throughout the day (*Xu* and *Qi*, 2001; *Jassal* et al., 2012), particularly, if T_s varies widely. At hourly and daily time scales, F_s has been shown to lag photosynthetic activity (*Baldocchi* et al., 2006). However, because the sensitivity of the F_s response to photosynthesis is relatively weak, the aforementioned time lag and the correlation between F_s and photosynthesis are often masked by stronger drivers such as T_s or *SWC* (*Davidson* et al., 1998; *Tang* et al., 2005; *Ruehr* et al., 2010). In addition, manual measurements are rarely performed daily, but usually every two to three weeks, sometimes even less frequently (*e.g.*, *Keith* et al., 1997; *Nouvellon* et al., 2012). Estimates of cumulative soil CO_2 flux (F_{sc}) are therefore obtained by interpolating F_s between two measurements using simple algorithms (*e.g.*, linear or cubic interpolation; *Savage* and *Davidson*, 2003; *Ryan* et al., 2010; *Nouvellon* et al., 2012), or by predicting missing values based on the relationship between F_s and other known variables (*e.g.*, soil temperature and water content; *Keith* et al., 1997; *Gomez-Casanovas* et al., 2013). Both of these interpolation methods generate uncertainties in F_{sc} estimates.

The general objective of this study was to highlight the effects of sampling frequency and sampling time on the estimation of F_{sc}. Firstly, datasets of recorded F_s with high and low within-day measurement frequencies were compared. Secondly, we compared the mean values of continuous automated measurements, taken over the time period typically used for manual measurements in the field with the mean values over each 24h period (for the same dataset). We hypothesized that one short measurement period during the day would not necessarily be representative of the mean daily flux if variations in T_s are large for a given day. Inversely, when diurnal variations in T_s are low, we assumed that F_s fluctuations should be negligible and measurements collected at any time during the day would be representative of the whole 24h period. Thirdly, we introduced artificial gaps of several days into the continuous datasets of automated measurements to obtain subsets with different time lags between two measurements (one to two weeks), similar to those that can be observed in manual measurement datasets. We used different methods to interpolate F_s within the gaps (either linear interpolations or empirical relationships between F_s, T_s, and *SWC*), and then evaluated the effect of the different measurement time steps on the resulting F_{sc} estimates and the biases associated with the different interpolation methods. We postulated that the best interpolation strategy and its related biases would depend on seasonal variations in temperature. We based our study on F_s data obtained from automated chambers at two contrasted sites: a eucalypt plantation characterized by a tropical climate and a poplar plantation with a temperate climate. Two datasets of automated F_s measurements with no missing data were used: a 12-month set for the eucalypt plantation and a 4-month set for the poplar plantation. Both periods included a wide range of T_s and *SWC* and encompassed several rain events.

2 Material and methods

2.1 Eucalypt plantation

The eucalypt plantation is located in Brazil (22°58′04′′S, 48°43′40′′W, 750m asl) in São Paulo State. The climate is tropical (Tab. 1). Soils are deep Ferralsols (*da Silva* et al., 2011). The plantation was established in November 2009. Soil CO_2 flux was measured continuously with a closed-path dynamic soil CO_2 flux system (Li-Cor 8100, Li-Cor, Inc., Lincoln, NE, USA) with four automated chambers (Li-Cor 8100-104, 20 cm diameter) connected to a multiplexer (Li-8150). CO_2 accumulation inside each chamber was measured every 30 min. The chambers were installed in June 2013 on collars inserted 2 cm into the soil. In the vicinity of each chamber, *SWC* and T_s were monitored continuously (one measurement every 30 min) with eight soil moisture probes (ECH2O-5, Decagon devices, Inc., Pullman, WA, USA) inserted to a depth of 5 cm and eight home-made thermocouples inserted to a depth of 8 cm.

2.2 Poplar plantation

The studied poplar plantation is located in northern France (Loiret, 47°48′25.5′′N, 1°58′36.1′′E, 110 m asl). The climate is temperate (Tab. 1). Soils are shallow Gleyic Luvisols. The plantation was established in March 2011.

Table 1: Main characteristics of the two experimental sites.

	Eucalypt plantation (Brazil)	Poplar plantation (France)
Annual precipitation / mm	1360	620
Mean annual temperature / °C	19	11
Soil (WRB classification)	Deep Ferralsol	Gleyic Luvisol
Clay:silt:sand[a] / %	17:3:80	9:22:69
C/N	17.9	11.8
pH	4.5	5.5
Species	*Eucalyptus grandis*	*Populus* × *euramericana*
Tree density / tree ha^{-1}	1666	1428
Previous land use	Two rotations of *E. grandis*	10 years of fallow land

[a]Soil characteristics are for the 0–50 cm soil layer.

Four home-made automated chambers (20 × 20 × 20 cm, made of acrylic resin) were installed in June 2011 on 5-cm high bases inserted into the top soil to a depth of 2 cm. They were connected to an IRGA (Li-840, Li-Cor, Inc., Lincoln, NE, USA). CO_2 accumulation in each chamber was recorded for 5 min every 90 min. In contrast to the 8100-104 chambers, our home-made automated chambers do not have pressure vents to prevent pressure gradients during measurements. The pressure difference between the outside and the inside of the chamber, that was measured continuously for several months using highly sensitive pressure sensors (GMSD 2.5 MR, Greisinger Electronic GmbH; Regenstauf; Germany; sensitivity 0.1 Pa), remained below 0.3 Pa. Biases related to the pressure pumping effect were therefore thought to be negligible (*Longdoz* et al., 2000). In the vicinity of the chambers, *SWC* and T_s were monitored continuously (one measurement every 5 min) with two water content reflectometers (CS616, Campbell scientific, Inc., Logan, UT, USA) and two home-made copper-constantan thermocouples inserted 10 cm into the soil. CO_2 accumulation, *SWC*, and T_s were recorded and stored on the data logger (CR3000, Campbell Scientific, Logan, UK, USA). The slopes of the linear increase in CO_2 concentrations over time inside the chamber were used to calculate F_s.

2.3 Comparison between soil CO_2 fluxes recorded at high and low frequencies within a day

In order to highlight the influence of the measurement frequency within a day on the estimation of mean daily F_s, we used F_s datasets recorded in the eucalypt plantation from June 19, 2013 to July 14, 2014, and in the poplar plantation from July 1 to November 2, 2013. We artificially built six data subsets from the original eucalypt dataset with measurements every 60, 90, 120, 180, 240, and 360 min, and two data subsets from the original poplar dataset with measurements every 180 and 360 min. Mean daily F_s was calculated by averaging all F_s values for each day and each dataset, and the resulting means were compared. We also established linear relationships between mean daily F_s obtained at the highest frequency (original dataset) and lower frequencies (built subsets). We used the lm function in R software (*R Core Team*, 2015) to test if the slopes and the intercepts were not significantly different from 1 and 0, respectively ($p \geq 0.05$).

2.4 Comparison between soil CO_2 fluxes averaged over 24 h and over shorter time periods

In order to test if F_s measurements recorded at any time of the day were representative of the mean daily F_s, F_s was averaged for each chamber over shifting time slots of 6 hours (corresponding to the duration typically reported for extensive manual field samplings). The interval between two consecutive time slots was set to the frequency at which the automated measurements had been taken leading to 48 and 16 six-hour shifting time slots per day at the eucalypt and poplar plantation, respectively. The relative deviations between each 6h-mean and mean daily F_s were calculated according to *Parkin* and *Kaspar* (2003) and averaged over a 391-day-long period for the eucalypt plantation and over a 125-day-long period for the poplar plantation.

2.5 Comparison between cumulative soil CO_2 fluxes (F_{sc}) obtained from complete datasets and F_{sc} from datasets with artificial gaps

To assess the effect on cumulative soil CO_2 flux (F_{sc}) of different interpolation options, we first created gaps in the datasets with no missing data from each automated chamber in order to mimic manual F_s datasets, in which sampling is much less frequent. We retained two time steps: one measurement every 7 d and one measurement every 14 d. From July 1, 2013 to June 30, 2014, *SWC* of the surface top soil ranged from 7 to 23% and T_s from 14°C to 25°C in the eucalypt plantation. From July 13 to October 21, 2013, *SWC* ranged from 5 to 30% and T_s from 10°C to 32°C in the poplar plantation (Fig. 1).

Two methods to interpolate the missing data within the gaps were then tested.

The first method was based on the linear interpolation of F_s between two measurement dates, t_1 and t_2:

$$F_S(t) = F_S(t_1) + (t - t_1)\frac{F_S(t_2) - F_S(t_1)}{t_2 - t_1}, \quad (1)$$

where F_s (t_1) and F_s (t_2) are the F_s values measured for days t_1 and t_2 ($t_1 < t < t_2$).

The second method was based on relationships between F_s, T_s, and *SWC*. For the tropical eucalypt plantation, we used the equation proposed by *Epron* et al. (2004) for such plantations:

$$F_S = a \times e^{[b(T_s-20)]} \times \left[1 - e^{(-d(SWC-c))}\right]. \quad (2)$$

For the poplar plantation, we used the equation proposed by *Vincent* et al. (2006) for soil with periods of water logging:

$$F_S = a \times e^{[b(T_s-10)]} \times e^{\left[-\left(\frac{\ln(SWC/c)}{d}\right)^2\right]}. \quad (3)$$

For both equations, *a, b, c*, and *d* are regression factors; *a* corresponds to F_s at optimal *SWC* and mean annual temperature (20°C for the eucalypt plantation and 10°C for the poplar plantation); *b* is a temperature sensitivity factor; *c* is the minimal *SWC* for F_s in Eq. (2) and the optimum *SWC* for F_s in Eq. (3); *d* describes the shape of the curve. We used the non-linear least squares method (using the nls function from package stats and the Gauss Newton algorithm for the numeric optimization) in R (*R Core Team*, 2015) to analyze the relationships between F_s, T_s, and *SWC*. We fitted the empirical equations with (1) *a, b, c*, and *d* parameters specific to each of the four chambers within a site, and (2) with the same *b, c*, and *d* parameters for the four chambers within a site, while only *a* differed. The empirical equations with the same *b, c*, and *d* parameters for all chambers were retained because they performed better (lower Akaike Information Criterion) than the ones with different parameters. Thus, parameters *b, c*, and *d* are characteristics of each site, while parameter *a* varies spatially among chambers within each site. We then

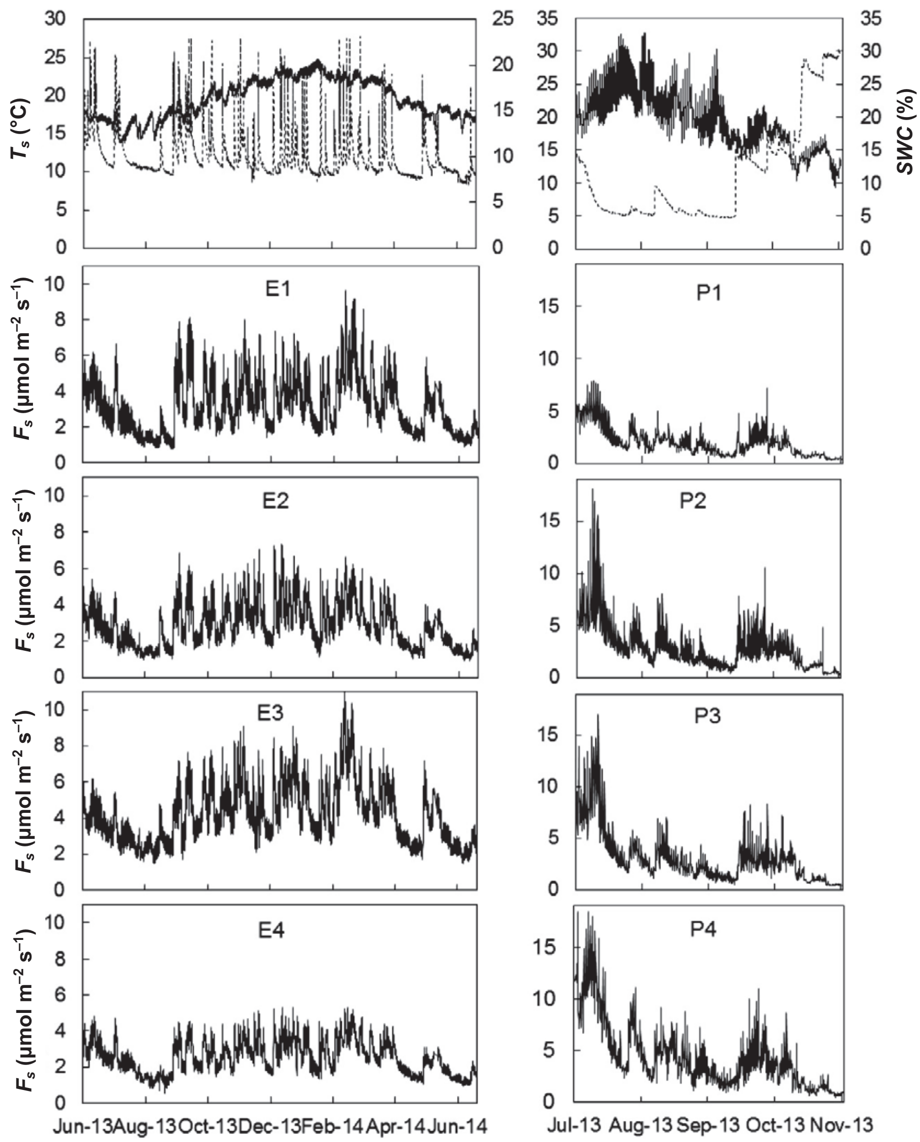

Figure 1: Soil temperature (T_s, continuous line), soil water content (*SWC*, dotted line) and soil CO_2 flux (F_s) in the four chambers from June 19, 2013 to July 14, 2014 in the eucalypt plantation (left) and from July 1 to November 2, 2013 in the poplar plantation (right).

calculated R^2 and the root mean square error (RMSE) to check that these empirical equations were well-fitted over the entire dataset at both sites, and we tested whether the slope of the linear relation between predicted and measured F_s was not significantly different from 1 and that the intercept was not significantly different from 0 at $p \geq 0.05$ using the lm function in R. The empirical equations fitted well daily F_s in both the tropical eucalypt plantation and the temperate poplar plantation (Tab. 2) with no bias in the distribution of the residuals. These equations were then fitted onto each subset and used to interpolate the missing data within the gaps.

For both interpolation methods, we compared the cumulative soil CO_2 flux obtained by summing all interpolated F_s values ($F_{sc\text{-}i}$) during the period from July 1, 2013 to June 30, 2014 in the eucalypt plantation and during the period from July 13 to October 21, 2013 in the poplar plantation, to the F_{sc} calculated by summing all measured daily F_s recorded during the same period.

3 Results

3.1 Temporal and spatial variations in soil CO_2 fluxes

In the eucalypt plantation, F_s decreased from June to mid September and then peaked at several occasions from the end of September to the end of March (Fig. 1). These abrupt increases in F_s followed rainfall events. The amplitude of the F_s response to an increase in *SWC* varied spatially among chambers. In the poplar plantation, F_s varied considerably between July 1 and November 2, 2013, with the highest F_s values measured in July, when both T_s and *SWC* were high (Fig. 1). The lowest F_s values were recorded at the end of October and in November, when T_s was low and *SWC* very high (the soil was waterlogged at that time). Marked differences in F_s were observed among the four chambers at each site (Fig. 1), indicating high spatial variability. This high spatial variability was also evidenced when we compared the adjusted *a* parameter from the four chambers at each site (Tab. 2). The

Table 2: Values of parameters *a, b, c*, and *d* and their standard error (SE) determined by fitting the two empirical models[Eq. (2)] and [Eq. (3)] describing relationships between daily F_s for the four chambers and both T_s and *SWC* at 10 cm in depth, using all data from July 1, 2013 to June 30, 2014 in the eucalypt plantation and from July 13 to October 21, 2013 in the poplar plantation. Values are shown with their coefficient of determination (R^2) and root mean square error (RMSE). The intercepts and the slopes of the linear regression between measured F_s and simulated values are shown. ^{NS} indicates that the intercepts and the slopes were not significantly different from 0 and 1, respectively.[a]

	E1	E2	E3	E4	P1	P2	P3	P4
a	5.5 ± 0.1	5.0 ± 0.1	7.2 ± 0.2	4.3 ± 0.1	1.7 ± 0.1	2.4 ± 0.2	2.5 ± 0.2	3.5 ± 0.2
b		0.09 ± 0.00				0.05 ± 0.01		
c		6.4 ± 0.1				11.9 ± 0.2		
d		0.29 ± 0.02				0.71 ± 0.02		
R^2		0.84				0.77		
RMSE		0.57				0.68		
Slope		1.00^{NS}				0.99^{NS}		
Intercept		$–0.01^{NS}$				0.04^{NS}		

[a]The temperature sensitivity factors (parameter *b*) correspond to *Q10* values of 2.4 and 1.7 for the eucalypt and the poplar site, respectively.

highest values were 67% and 106% higher than the lowest ones in the eucalypt and poplar plantations, respectively.

3.2 Comparison between soil CO_2 fluxes recorded at high and low frequencies within a day

For the eucalypt plantation, mean daily F_s values estimated from a dataset with a frequency of one measurement every 360 min were similar to those obtained with the highest frequency (one measurement every 30 min). In the poplar plantation, one measurement every 180 min was the lowest frequency to provide similar mean daily F_s values to those obtained with the highest measurement frequency (Fig. 2). For lower sampling frequencies, the slope and the intercept of the linear regression became significantly different from 1 and 0, respectively, and the R^2 fell below 0.95 (data not shown).

3.3 Comparison between soil CO_2 fluxes averaged over 24h and over shorter time periods

In the eucalypt plantation, daily F_s estimated by averaging values obtained over 6-hour periods were similar to those obtained by averaging over 24 hours (Fig. 3), with relative deviations of CO_2 flux ranging from –4% to 7%. For 40 of the 48 time slots tested, the deviations ranged from –5% to 5%. The best estimates were obtained for the 10:00-to-16:00 (13:00 for the center of the 6-hour periods) and the 19:00-to-01:00 time slot with a deviation of –0.1%.

In the poplar plantation, where large daily variations in T_s were observed especially during summer (Fig. 3), the 6h-mean F_s and 24h-mean F_s differed more than in the eucalypt plantation.

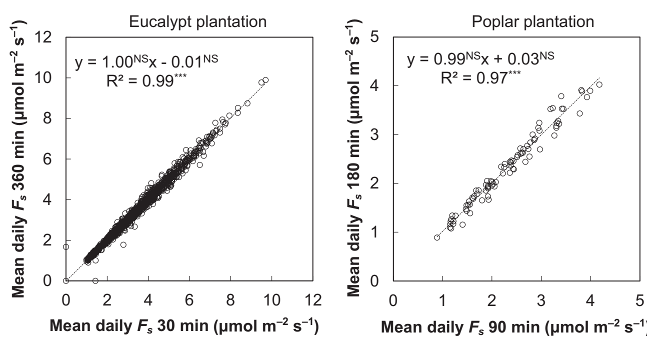

Figure 2: Comparison between mean daily F_s (estimated after averaging all F_s values recorded every 30 min) and mean daily F_s (estimated after averaging all F_s values recorded every 360 min) in the eucalypt plantation from June 19, 2013 to July 14, 2014 (left), and comparison between mean daily F_s (estimated after averaging all F_s recorded every 90 min) and mean daily F_s (estimated after averaging all F_s recorded every 180 min) in the poplar plantation from July 1 to November 2, 2013 (right). The equation and R^2 of the linear regression are shown. ^{NS} indicates that the slope and the intercept are not significantly different from 1 and 0, respectively, at $p = 0.05$. *** indicates that R^2 is significantly different from 0 at $p = 0.001$.

For 9 of the 16 time slots tested, the 6h-mean deviates from the 24h-mean CO_2 flux by more than 10% (Fig. 3). The best estimates were obtained from 6:00 to 12:00 with daily F_s overestimated by 1%, and from 16:30 to 22:30 with daily F_s underestimated by 0.2%. The worse estimate was obtained when averaging data from 10:30 to 16:30 with daily F_s overestimated by almost 20%.

A clockwise hysteresis was observed between the relative deviation in T_s and the relative deviation in F_s at both sites

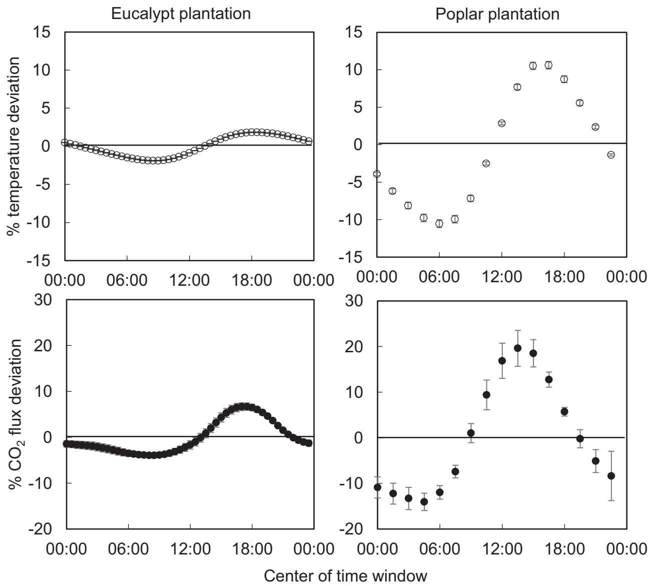

Figure 3: Mean diurnal patterns of soil temperature and CO_2 flux averaged over 6-hour periods (times on the x-axis is the center of the periods) and expressed as the relative deviation from the 24-h daily average, from June 19, 2013 to July 14, 2014 in the eucalypt plantation (left), and from July 1 to November 2, 2013 in the poplar plantation (right). For temperature deviation, error bars indicate standard errors of the mean of 391 days for the eucalypt plantation and 125 days for the poplar plantation. For CO_2 flux deviation, error bars indicate standard errors of the mean of the four chambers at each site. Small bars are sometimes obscured by the symbol.

with an increase in F_s more rapid than the increase in T_s during day-time, and a decrease in F_s more rapid than the decrease in T_s during night-time (Fig. 4). The maximal positive deviation of F_s occurred three hours before the maximal positive deviation of T_s. in the poplar plantation. The hysteresis was less pronounced in the eucalypt plantation than in the poplar plantation, with the lag between F_s and T_s of less than one hour.

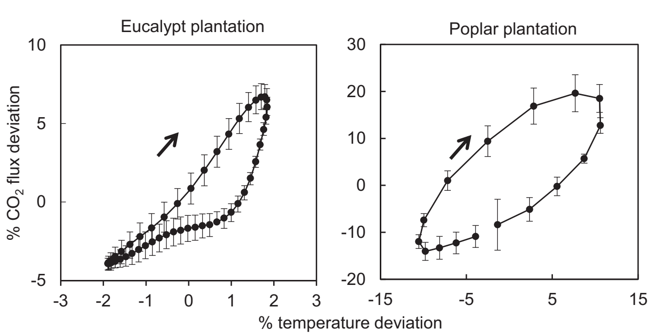

Figure 4: Relationships between CO_2 flux and soil temperature, averaged over 6-hour periods, expressed as the relative deviation from the 24-h daily average, from June 19, 2013 to July 14, 2014 in the eucalypt plantation (left), and from July 1 to November 2, 2013 in the poplar plantation (right). Vertical error bars indicate standard errors of the mean of the four chambers at each site. The arrows indicate the direction of the hysteresis. Scales are different for the two plots.

3.4 Comparison between cumulative soil CO_2 fluxes obtained from complete datasets and from gapped datasets

With gaps of seven days, mean $F_{sc\text{-}i}$ values (averaged over the gapped subsets) were very close to F_{sc} for both interpolation methods, with limited variation among the subsets (Fig. 5). The interquartile ranges (IQR) were within 1–2% of F_{sc} for the eucalypt plantation and 4–7% for the poplar plantation. When one F_s measurement was kept every 14 d, the mean values of $F_{sc\text{-}i}$ were also very close to the F_{sc}, but with a larger IQR (2–4% for the eucalypt plantation and 8–14% for the poplar plantation). At both sampling frequencies, the linear interpolation and the empirical model had similar performance in the eucalypt plantations. The linear interpolation performed better than the empirical model in the poplar plantations, especially when one F_s measurement was kept every 14 d (IQR of 13–25%).

4 Discussion

4.1 Temporal and spatial variations in soil CO_2 flux

Our measurements confirmed that spatial heterogeneity remains the dominant source of uncertainty in estimating F_{sc} at the stand level. Increasing the number of chambers is the only way to reduce sampling uncertainties due to spatial heterogeneity (*Savage* et al., 2008). We were unable to calculate the minimum number of chambers necessary for our study sites with only four chambers. However, our results show that daily variations in F_s can be captured with low frequency measurements (one measurement every 360 min for the eucalypt plantation and one measurement every 180 min for the poplar plantation). This means that more automated chambers sharing the same gas analyzer can be set up within a site without altering the accuracy of the estimation of mean daily F_s. However, it remains challenging to satisfactorily cover the spatial variability of F_s with automated chambers, especially because of limitation in tube length, and this is why, in many experimental sites covering large areas or including several treatments, manual chambers—which provide spatially representative data—are still used to estimate F_{sc}.

4.2 Effect of measurement time on estimation of daily soil CO_2 flux

In most studies, it is assumed that measurements averaged over a several-hour period are representative of the daily flux, but this assumption could be inaccurate. Different factors could be driving the daily variation in F_s. In our young temperate poplar site, daily F_s can be overestimated or underestimated by a factor of up to 20% (0.6 μmol m^{-2} s^{-1} on average) when using data averaged over 6 hours rather than data averaged over 24 hours. The two periods from 6:00 to 12:00 and from 16:30 to 22:30 provided the most accurate estimation of daily F_s (overestimation of about 1% and underestimation of about 0.2%, respectively). For the tropical site, which exhibited less pronounced diurnal variations in T_s than the temperate site, measurements averaged over any 6h period were well related to the daily flux.

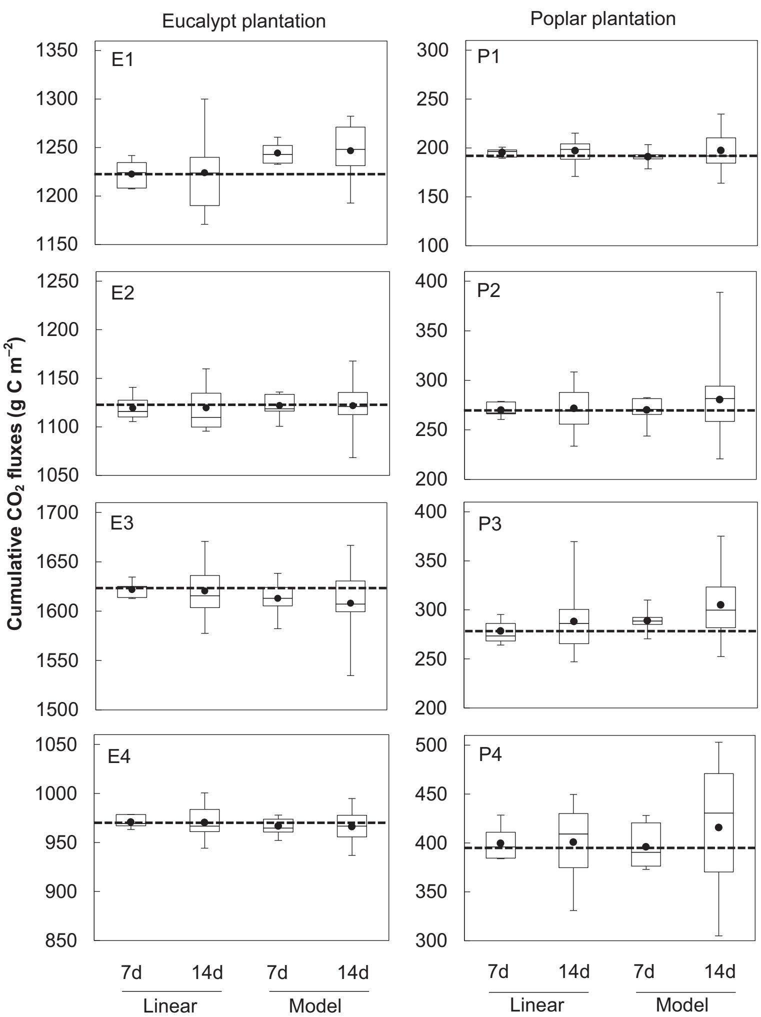

Figure 5: Cumulative CO_2 flux (horizontal dashed line), calculated by summing all daily F_s values from July 1, 2013 to June 30, 2014 in the eucalypt plantation (chambers E1 to E4) and from July 13 to October 21, 2013 in the poplar plantation (chambers P1 to P4), and averaged cumulative CO_2 flux (box-plots) estimated after gap-filling artificial datasets, keeping one measured F_s value every 7 days (7d) and every 14 days (14d). Gap-filling was either done by linear interpolation between two consecutive retained measurements or with empirical relationships (models) between soil CO_2 flux and both soil temperature and soil water content. The thin solid line in the box-plots indicates the median of the raw data and the dot indicates the mean. The top and bottom of the boxes indicate the 25th and the 75th percentiles. The whiskers above and below the boxes indicate maximum and minimum values.

Hysteresis between T_s and F_s was pronounced in the poplar plantation, where F_s maximum preceded T_s maximum by three hours. Similar shifts were previously observed in a corn–soybean cropping system (*Parkin* and *Kaspar*, 2003) and in a mixed conifer forest (*Vargas* and *Allen*, 2008). Diurnal variations in air temperature are usually more pronounced in temperate areas than in tropical ones, and canopy openness also accounted for the difference in the daily amplitude in T_s between our two sites. Indeed, the eucalypt canopy was more closed and the layer of litter on the forest floor was thicker than in the younger poplar plantation. Smaller diurnal variations in F_s at the eucalypt site may also result from the deep rooting of this species in sandy soils (*Christina* et al., 2011; *Laclau* et al., 2013). Longer transportation distances from deeper soils and larger CO_2 storage capacity in the soil are likely to buffer the diurnal variability in F_s (*Maier* et al., 2011).

At the eucalypt site, all of the 6h time slots convenient for collecting manual measurements in the field (starting after 8:00 and finishing before 17:00) provided good estimates of daily F_s, though the most accurate measurements were recorded between 10:00 and 16:00 and between 19:00 to 1:00 (0.1% underestimation for both periods). Similarly, *Yan* et al. (2006) found that measurements recorded between 9:00 and 12:00 provided very good estimates of 24-hourly mean F_s in three subtropical forests at different successional stages. On the other hand, *Savage* and *Davidson* (2003) found that extrapolations of mid-morning measurements underestimated by 13% the daily flux obtained by summing the 24 hourly measurements in a mixed hardwood temperate forest, while daytime measurements overestimated the daily flux by 4–6% in a young pondesora pine plantation (*Xu* and *Qi*, 2001). Higher fluxes during the day than during the night have also been observed in a longleaf pine savannah (*Ford* et al., 2012). The assumption that data collected over a short period of time are representative of the daily flux could therefore result in a wrong estimation of F_{sc} for temperate forests (*Lee* et al., 2002). In such situations, continuously monitoring F_s with a few automated chambers is a good option in sites with large within-day variations in T_s, either to select the best time slot for manual measurements, or to correct manual measurements taken during the day with more numerous chambers.

4.3 Effects of sampling time step and interpolation method on cumulative soil CO_2 flux (F_{sc}) estimation

Manual F_s measurements are commonly performed only once a week or every two weeks, and sometimes even less frequently (*e.g.*, once a month). Though a low within-day sampling frequency had a limited impact on the estimation of mean daily F_s, the within-year sampling time step had a much stronger impact on the estimation of F_{sc}. This indicates that the drivers of F_s are not the same at the daily timescale as at the seasonal scale. Furthermore, the sampling time step that provides the best estimate of seasonal or annual CO_2 flux may differ among sites. For example, *Savage* et al. (2008) found that a manual sampling strategy with a two-week time step was sufficient in a mixed hardwood forest and in a boreal transition forest, while *Parkin* and *Kaspar* (2004) found that more frequent measurements were needed on agricultural soils.

F_{sc} is often estimated with linear interpolation of F_s between two measurements or with empirical relationships between daily F_s and T_s and/or *SWC* (*Keith* et al., 1997; *Subke* et al., 2003). In our study, for the datasets mimicking one measurement per week, all $F_{sc\text{-}i}$ obtained after linear interpolation between measurement dates were within 3% for eucalypt and 10% for poplar (Fig. 5) of the F_{sc} calculated using all the values measured daily. In contrast, for datasets mimicking one measurement every two weeks in the poplar plantation, only 40% of the $F_{sc\text{-}i}$ values obtained after linear interpolation between measurement dates and 50% of the $F_{sc\text{-}i}$ values obtained using the empirical equation were within 10% of F_{sc}. In the eucalypt plantation, this sampling frequency was still sufficient to provide accurate cumulative fluxes (96% of $F_{sc\text{-}i}$ values within 5% of F_{sc} with linear interpolation and 98% using the empirical equation). Why model-based interpolation does not perform better than linear interpolation is that model parameters may vary seasonally (*Gomez-Casanovas* et al., 2013), being modified by several climate-driven or phenology-driven factors. Spectral analyses are required to address the performance of these empirical equations to detect at which time scale biases between predictions and observations are occurring (*Dietze* et al., 2011).

Linear interpolation was therefore a robust interpolation option when F_s was measured weekly in the temperate plantation and every week or two weeks in the tropical plantation, providing in both cases accurate cumulative fluxes without the need for the continuous monitoring of T_s and *SWC* that are required for interpolation methods based on empirical equations. However, this presupposes that there is no systematic bias (*e.g.*, measurements never taken after a rain event). Empirical relationships may, however, still be a reliable method for interpolating F_s, depending on their ability to capture the responses of F_s to rapid modifications in *SWC* when using a short time-step dataset (*Savage* and *Davidson*, 2001).

5 Conclusion

Large spatial and temporal variations in F_s occur in most ecosystems. Two independent, complementary methods are typically used to measure F_s: data from automated chambers make it possible to estimate the temporal variability in F_s at a fine time scale (hourly), and manual chamber measurements account for spatial variability. On the basis of our results, we recommend combining both methods. Automated chamber measurements help to determine the best time slot during which manual measurements should be performed (*i.e.*, when F_s values averaged over the slot are similar to mean daily F_s), or to correct F_s values averaged over other time slots. They can also help to elaborate empirical equations that can then be used to extrapolate F_s measurements based on continuous records of T_s and *SWC*. Ideally, automated chambers should be positioned across the plot to reflect F_s spatial variability. The within-day sampling frequency for automated measurements can be quite low, while still providing accurate estimations of mean daily F_s. This could allow more automated chambers to be installed at a given site, thus, ensuring better coverage of spatial heterogeneity. Spectral analyses on biases between modelled and measured F_s with a limited number of automated chambers may provide concrete guidelines for implementing manual measurement protocols and for selecting the best interpolation strategies. Thus, combining both approaches will improve our ability to estimate cumulative soil respiration at the ecosystem scale, a prerequisite for the reliable evaluation of annual carbon budgets in forest soils and for a better understanding of the dynamics of belowground carbon allocation.

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