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Carbon balance of a three crop succession over two cropland sites in South West France

Béziat Pierre, Ceschia Eric *, Dedieu Gérard

Centre d'Études Spatiales de la Biodiversité (CESBIO), 18 Avenue Edouard Belin bpi 2801, 31401 Toulouse Cedex 9, France

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ABSTRACT

Long term flux measurements of different crop species are necessary to improve our understanding of management and climate effects on carbon flux variability as well as cropland potential in terrestrial carbon sequestration. The main objectives of this study were to analyse the seasonal dynamics of CO₂ fluxes and to establish the effects of climate and cropland management on the annual carbon balance. CO₂ fluxes were measured by means of the eddy correlation (EC) method over two cropland sites, Auradé and Lamasquère, in South West France for a succession of three crops: rapséed, winter wheat, and sunflower at Auradé, and triticale, maize and winter wheat at Lamasquère. The net ecosystem exchange (NEE) was partitioned into gross ecosystem production (GEP) and ecosystem respiration (R) and was integrated over the year to compute net ecosystem production (NEP). Different methodologies tested for NEP computation are discussed and a methodology for estimating NEP uncertainty is presented.

NEP values ranged between −369 ± 33 g C m⁻² y⁻¹ for winter wheat at Lamasquère in 2007 and 28 ± 18 g C m⁻² y⁻¹ for sunflower at Auradé in 2007. These values were in good agreement with NEP values reported in the literature, except for maize which exhibited a low development compared to the literature. NEP was strongly influenced by the length of the net carbon assimilation period and by interannual climate variability. The warm 2007 winter stimulated early growth of winter wheat, causing large differences in GEP, R, and NEE dynamics for winter wheat when compared to 2006. Management had a strong impact on CO₂ flux dynamics and on NEP. Ploughing interrupted net assimilation during voluntary re-growth periods, but it had a negligible short term effect when it occurred on bare soil. Re-growth events after harvest appeared to limit carbon loss; at Lamasquère in 2005 re-growth contributed to store up to 50 g C m⁻². Differences in NEE response to climatic variables (VPD, light quality) and vegetation index were addressed and discussed.

Net biome production (NBP) was calculated yearly based on NEP considering carbon input through organic fertilizer and carbon output through harvest. For the three crops, the mean NBP at Auradé indicated a nearly carbon balanced ecosystem, whereas Lamasquère lost about 100 g C m⁻² y⁻¹; therefore, the ecosystem behaved as a carbon source despite the fact that carbon was imported through organic fertilizer. Carbon exportation through harvest was the main cause of this difference between the two sites, and it was explained by the farm production type. Lamasquère is a cattle breeding farm, exporting most of the aboveground biomass for cattle bedding and feeding, whereas Auradé is a cereal production farm, exporting only seeds.

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1. Introduction

Understanding and quantifying carbon sources and sinks is a major challenge for the scientific community. The main goal is to assess the carbon balance, to see what practices result in lower emissions and to recommend their use. In terrestrial ecosystems, the massive conversion of forest to cropland has caused an important loss of soil carbon, mainly through soil respiration (Robert and Saugier, 2003). Currently, croplands represent about one third of Europe’s land surface (Smith et al., 2005). Over the last 8000 years, agriculture has had a significant impact on the atmospheric concentration of CO₂ and CH₄ (Salinger, 2007). Impacts of agriculture on global climate changes through greenhouse gas emissions and changes in the physical properties of land cover have been summarized in the recent analyses of Desjardins and Swackhamer (2007) and Raddatz (2007). Hutchinson et al. (2007) concluded that the carbon sequestration potential of croplands should be considered as a modest but non-negligible contribution to climate change mitigation (between 3% and 6% of fossil fuel contribution to climate changes), but quantification of

* Corresponding author. Tel.: +33 5 61 55 85 27; fax: +33 5 61 55 85 00.
E-mail address: eric.ceschia@cesbio.cnrs.fr (C. Eric).

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crop carbon sequestration potential remains very uncertain. Therefore, variability in stocks and fluxes of carbon in croplands is a theme of major interest. However, most studies involving micrometeorological measurements by the eddy correlation (EC) method have focused on forest ecosystems, some have investigated grasslands and only a minority has concentrated on croplands.

Recent studies on croplands have focused on seasonal patterns of CO₂ flux and annual carbon balance for different crops. The most studied croplands were maize-soybean rotations in North America (Baker and Griffis, 2005; Bernacchi et al., 2005; Hollinger et al., 2005; Pattey et al., 2002; Suyker et al., 2005, 2004; Verma et al., 2005). However, rice (Saito et al., 2005), sugar beet (Moureaux et al., 2006), winter wheat and triticale (Ammann et al., 1996; Anthoni et al., 2004a; Baldocchi, 1994) have also been studied. In Soegaard et al. (2003), an attempt was made to scale up crop fluxes by comparing EC measurements placed on a tall mast coupled with a footprint analysis of EC measurements over five different crop plots (winter wheat, spring and fall barley, maize and grass) around the tall mast.

Some of recent studies on croplands reveal the importance of management practices on plot carbon balance. In Baker and Griffis (2005), CO₂ flux measurements were carried out on two plots with similar climatic and soil conditions but different management practices. The authors concluded that carbon gain caused by reduced tillage and intercropping compared to conventional management was compensated for by a drop in productivity and an increase in crop residue decomposition. However, it has been shown that the conversion of conventional tillage to no-till agriculture in maize/soybean crops in the USA might result in an annual net carbon sequestration of 20.77 Tg C (Bernacchi et al., 2005, 2006). Hollinger et al. (2005) showed that considering biomass export and fuel combustion may transform a soybean crop from a sink to a source of carbon. Therefore, considering management to address whether a crop is a source or a sink is essential.

Still, too few long-term accurate flux measurements over different crop species have been conducted to quantify management and climate effects on spatial and temporal flux variability, as well as to determine the potential role of cropland in terrestrial carbon sequestration.

In the present study, CO₂ flux measurements were performed, using the EC method, during three cropping seasons in South West France at two crop sites with similar climates but different soils and management practices. The main objectives were (1) to adapt conventional EC data post-treatments, developed mainly for forest, to account for fast and discontinuous canopy structure variations specific to croplands, to evaluate the impact of these modified computational methods on annual net ecosystem carbon exchange (NEP) and estimate NEP uncertainty; (2) to analyse the seasonal dynamics and CO₂ flux evolution of different crop species (rapeseed, triticale, winter wheat, maize and sunflower) in relation to management and climate; (3) to compare crop carbon assimilation efficiencies through analysis of light response curves; and (4) to establish the annual carbon balance for the different crops and evaluate the influence of management and climate.

2. Materials and methods

2.1. Site descriptions

Since 18 March 2005, micrometeorological and meteorological measurements have been performed on two cultivated plots, Auradé and Lamasquère, separated by 12 km and located near Toulouse (South West France). Both sites are part of the CarboEurope-IP Regional experiment (Dolman et al., 2006) and the CarboEurope-IP Ecosystem component (WP1) experiment.

Both sites have been cultivated for more than 30 years and experience similar climatic conditions but have different management practices, soil properties and topography. Crop rotations on both sites are quite representatives of the main regional crop rotations. Table 1 summarizes the main characteristics and general climate of the two sites.

The Auradé plot belongs to a private farmer and is located on a hillside area near the Garonne river terraces. The plot is characterised by a rapeseed/winter wheat/sunflower/winter wheat rotation. It was cultivated with rapeseed (Brassica napus L.) from 13-Sept-2004 to 27-Jun-2005, with winter wheat (Triticum aestivum L.) from 27-Oct-2005 to 29-Jun-2006 and with sunflower (Helianthus annuus L.) from 11-Apr-2007 to 20-Sep-2007. It was supplied with mineral fertilizer (204 and 124 kg N ha⁻¹ for rapeseed and winter wheat, respectively, and no fertilization for sunflower) and has never been irrigated. Superficial tillages (5–10 cm depth) were done after rapeseed harvest (04-Jul-2005 and 04-Aug-2005) to plough residues and re-growth of crops and weeds into the soil. Deep tillages (30 cm depth) were performed before winter wheat sowing (22 and 23-Sep-2005) and before sunflower sowing (plough on 29 and 30-Sep-2006 and harrow on 12-Mar-2007).

The Lamasquère plot is cultivated with triticale (Triticosecale) from 24-Nov-2004 to 11-Jul-2005, with maize (Zea Mays L.) used for silaging from 01-May-2006 to 31-Aug-2006 and with winter wheat (Triticum aestivum L.) from 18-Oct-2006 to 15-Jul-2007. This plot is part of an experimental farm owned by the Ecole Supérieure d’Agronomie de Purpan (ESAP). The instrumented site borders the “Touch” river and is characterised by a triticale/maize/winter wheat/maize rotation. Organic fertilisers (150, 115 and 150 kg N ha⁻¹ for triticale, maize and winter wheat, respectively) and mineral fertilisers (89, 91 and 234 kg N ha⁻¹ for triticale, maize and winter wheat, respectively) were supplied to the plot. To plough residues and manure into the soil, the plot was tilled superficially before the sowing of triticale (28-Sep-2004), and a non-inverting tillage was performed between the maize harvest and winter wheat sowing (10 and 11-Oct-2006). A deep tillage was done before maize sowing (plough on 01-Dec-2005 and harrow on 29 and 30-Mar-2006). The plot was irrigated when maize was cultivated, with a total amount of 147.8 mm. In autumn 2004, triticale seeds were spread instead of being sown in a row, because the soil was too wet to allow the use of conventional tools.

2.2. Flux measurements

2.2.1. Flux measurements

Masts were installed in the middle of each plot in order to optimize fetch in main wind directions (see Table 1). Secured enclosures surrounded the masts to avoid damage caused by wild animals. Management within the enclosures closely resembled the management in the rest of the fields. Turbulent fluxes of CO₂ (Fco₂), water vapour (evapotranspiration, E and latent heat, LE), sensible heat (H) and momentum (T) were measured continuously by the EC method (Aubinet et al., 2000; Baldocchi, 2003; Grelle and Lindroth, 1996; Moncrieff et al., 1997) since 18-Mar-2005. The EC devices were mounted at heights of 2.8 and 3.65 m at Auradé and Lamasquère, respectively. Instrument heights were chosen to be at worst 1 m higher than crops at their maximum development. The EC system is made of a three-dimensional sonic anemometer (CSAT 3, Campbell Scientific Inc, Logan, UT, USA) and an open-path infrared gas analyzer (LI7500, LiCor, Lincoln, NE, USA). Data were recorded at 20 Hz on a data logger (CRS000, Campbell Scientific Inc, Logan, UT, USA) and stored on a 1 GB compact flash card. Zero and span calibrations were performed for CO₂ and H₂O every six month.
2.2.2. Meteorological measurements

Standard meteorological variables were recorded on each site to analyse and calculate turbulent fluxes. Different radiation components were measured: incoming and outgoing short-wave and long-wave radiation with a CNR1 (Kipp & Zonen, Delft, NL); net radiation with a NR-lite (Kipp & Zonen, Delft, NL); incoming photosynthetic photon flux density (PPFD) with a PAR-lite (Kipp & Zonen, Delft, NL) and direct and diffuse PPFD with a BF2 (Delta-T, Cambridge, UK). Direct and diffuse PPFD measurements began in March 2005 at Lamasque`re and in September 2005 at Auradé`. Three PAR-LE sensors (PAR-LE, Solems, Palaiseau, France) were used to measure transmitted PPFD to soil and one to measure reflected PPFD above vegetation. Photosynthetic photon flux density absorbed by vegetation (aPPFD) was calculated as follows (Ruimy et al., 1995):

\[ aPPFD = (PPFD + rTPPFD) - (tPPFD + rTPPFD) \]  

where rs is the soil reflectance for PPFD, tPPFD is the PPFD transmitted to soil and rtPPFD is the total reflected PPFD by both soil and vegetation measured above vegetation. The first and second term of the right-hand side of Eq. (1) correspond to incoming and outgoing PPFD relative to the vegetation, respectively. rs was estimated as the slope of the linear regression between rtPPFD and PPFD during bare soil periods between tillage and sowing. rs estimates were 0.145 ($R^2 = 0.81$) at Lamasque`re and 0.231 ($R^2 = 0.82$) at Auradé`. aPPFD was only calculated for periods with plant area index (PAI) higher than 1 m$^2$ m$^{-2}$ to limit spatial variability errors in tPPFD measurements caused by spatial heterogeneity in radiation at the floor and the limited number of sensors. During those periods, statistical differences between the PAR-LE sensors were low (relative standard deviation <0.3).

Air temperature and relative humidity were measured with a Vaisala probe (HMP35A, Vaisala, Helsinki, Finland). Precipitation was recorded with a ARG100 rain-gauge (Environmental Measurements Ltd., Sunderland, UK). atmospheric pressure with a BS4 sensor (BS4, Delta-T, Cambridge, UK), wind speed and direction with a 014A wind speed sensor and a 024A wind direction sensor (Met one instruments, inc., Grants Pass, OR, USA), respectively, at Lamasque`re and a Young wind monitor (05103, Young, Traverse city, MI, USA) at Auradé`. Surface radiative temperature was measured with a precision infrared temperature sensor (IRTS-P, 153...173).
2.2.3. Biomass inventories and photosynthetic surface measurements

Destructive measurements were operated to analyse biomass and PAI dynamics. In 2005, randomly spatially distributed plants were collected monthly in each field. Between each destructive measurement date, 30 and 20 randomly spatially distributed hemispherical photographs were taken at Crozat and Laumasqère, respectively, to analyse PAI temporal evolution more accurately (Demarez et al., in press). This method was cross-calibrated with destructive measurements. In 2006 and in 2007, plants were collected on the two diagonals of the fields, monthly during slow vegetation development periods and every two weeks during fast vegetation development periods. The aboveground dry mass (DM) distribution among organs was measured using OHAUS balance (SPU 4001, OHUSA, Pine Brook, NJ, USA). PAI was defined as the half surface of all green organs and leaf area index (LAI) as the half surface of green leaves; it was measured by means of a LiCor planimeter (LI3100, LiCor, Lincoln, NE, USA). For rapeseed, maize and sunflower, 30 plants were collected at each date. However, because of the large rapeseed plant sizes, only 10 plants were sampled at Auradé from April 2005 until harvest. This reduced sampling and the large variability observed in the field may explain the large PAI standard deviation observed on 28-April-2005 (Fig. 2(a)). For winter wheat, 1.5 m long rows were collected at each sampling date. Because seeds were not sown in rows, triticate was sampled by collecting ten 0.25 m² plots.

After harvest, crop residues were sampled on ten 0.25 m² plots for each crop. Analyses of plant and residue carbon content were performed just before harvest. Exported carbon from the plot and residue during harvest (Exp) was calculated by subtracting the carbon content in the aboveground biomass (AGB) and the carbon content in crop residues (Residues). Exp standard deviation, \( \sigma(\text{Exp}) \), was calculated from \( \sigma(\text{AGB}) \) and \( \sigma(\text{Residues}) \) as:

\[
\sigma(\text{Exp}) = \sqrt{\frac{\sigma(\text{AGB})^2 + \sigma(\text{Residues})^2}{\text{nb}}} \quad (2)
\]

where nb is the number of aboveground biomass samples, and nr the number of residues samples. For this calculation, we assume a normal distribution and independence between AGB and Residues. We choose to calculate Exp from our destructive samples instead of using the yield data from the farmers, because their yield estimates correspond to mean yield values for several plots grown with the same crop on the farm. However, both Exp and Residues were in good agreement (slope = 0.97, intercept = 19 g C m⁻², \( R^2 = 0.98 \)).

2.3. Flux data treatments

2.3.1. Flux calculation

Atmospheric convention was used in this paper with negative flux moving downward from the atmosphere to the ecosystem and positive flux moving upward. EdiRe software (Robert Clement, © 1999, University of Edinburgh, UK) was used to calculate fluxes on 5 and 30 min intervals following CarboEurope-IP recommendations. A 2D rotation was applied in order to align the streamwise wind velocity component with the direction of the mean velocity vector. Fluxes were corrected for spectral frequency loss (Moore, 1986). \( F_{\text{EC}}, F \) and \( LE \) fluxes were corrected for air density variations (Webb et al., 1980).

Before temperature, relative humidity and CO₂ concentration profiles below the EC system were measured, changes in CO₂ storage (\( F_{\text{EC}} \)) were calculated as described in Aubinet et al. (2001) but with only one measuring height for CO₂ concentration:

\[
F_{\text{EC}} = \frac{P_{\text{ec}}}{C_3} \frac{\Delta T}{T_h} \frac{\Delta h}{h_0} \quad (3)
\]

where \( P_{\text{ec}} \) is the EC system height, \( P_3 \) is the atmospheric pressure at \( h_0 \), \( T_h \) is the air temperature at \( h_0 \), \( R \) is the molar gas constant, and \( C_3 \) is the CO₂ concentration at \( h_0 \). This methodology is known to underestimate \( F_{\text{EC}} \) by about 20–25% (Saito et al., 2005). However, it is often used for ecosystems with short vegetation, such as croplands and grasslands, where \( F_{\text{EC}} \) is assumed to be low (Anthoni et al., 2004a; Moureaux et al., 2006; Suyker et al., 2005; Verma et al., 2005; Wohlfarth et al., 2005; Xu and Baldocchi, 2004). Net ecosystem exchange (NEE) was then calculated as the sum of \( F_{\text{EC}} \) and \( F \). When CO₂ concentration profiles below the EC were measured, Eq. (3) was used to calculate storage in each \( h_l \) high layer of the profile. \( F_{\text{EC}} \) below the EC system was then calculated as the sum of storage in each \( h_l \) high layer.

2.3.2. Flux filtering and quality control

Fluxes were filtered to remove data corresponding to technical problems, inappropriate meteorological conditions for EC measurements, low spatial representativeness, and violation of EC theory (Aubinet et al., 2000; Baldocchi, 2003; Foken and Wichura, 1996).

Initially, flux data were discarded if the scalar means, scalar standard deviations or flux values were out of realistic bounds. \( F_{\text{EC}}, F \) and LE were also discarded during rainfall periods and the half-hour following rainfall events because of a dysfunction of the open-path gas analyzer and sonic anemometer in wet conditions. However, Ruppert et al. (2006) showed that rain gauge measurements are not sufficiently accurate to identify light precipitation events; therefore, outliers remain. In the present study, these remaining outliers, as well as those caused by the wet gas analyzer or other events, were detected by the comparison of half-hourly fluxes \( X_l \) with a 200 data point moving mean (\( X_{200} \)) and standard deviation (\( X_{200} \)) as follows:

\[
\text{if } X_l < X_{200} - (2.5 \cdot X_{200}) \quad \text{(4a)}
\]

or

\[
\text{if } X_l > X_{200} + (2.5 \cdot X_{200}) \quad \text{(4b)}
\]

then \( X_l \) was discarded from the dataset. This procedure was performed separately for day-time and night-time data. Night-time was defined as \( PFD < 5 \mu \text{mol m}^{-2} \text{s}^{-1} \) and solar elevation angles < 90°.

A friction velocity (\( u^* \)) criteria was used to determine periods within the low turbulence regime when fluxes are systematically underestimated by EC measurements (Aubinet et al., 2000; Falge et al., 2001; Gu et al., 2005; Papale et al., 2006; Reichstein et al., 2005). Reichstein et al. (2005) proposed an automatic method to determine the \( u^* \) threshold applied every three months to take into account changes in phenology and canopy properties. However, in croplands, changes in canopy structure are fast and discontinuous because of harvest and tillage. Therefore, we defined crop functioning periods (CPF) between dates of sowing, maximum crop development, harvest and tillage. A \( u^* \) threshold was then...
determined with the Reichstein et al. (2005) automatic method for each CFP. Flux data below the highest $u_*$ threshold were discarded from the dataset to maintain the same conservative approach as Reichstein et al. (2005).

For each half-hourly flux value, a fetch including 90% of the flux $(D_{0.9})$ was computed with the Kljun et al. (2004) parameterisation. This fetch was compared with the distance between the mast and the edge of the plot in the main wind direction for the corresponding half-hour $(D_i)$. If $D_{0.9} > D_i$, fluxes were discarded because we assumed that it was not sufficiently representative of the plot.

Stationarity and development of turbulent conditions are important hypotheses for EC measurements. They were tested with the steady state test and the integral turbulence characteristic test recommended by Foken and Wichura (1996) and revisited by Foken et al. (2004). Flux data were flagged 0, 1 or 2 with 0 corresponding to the best quality and 2 to the worst (see Foken et al. 2004 for details). However, the steady state test was applied only if an absolute threshold between covariance over 30 min and means of covariances over 5 min for the corresponding half-hour was reached. This method allows us to keep fluxes corresponding to covariances close to zero that failed the steady state test for mathematical reasons. The absolute threshold was defined as the EC measurement estimated accuracy; it was fixed, based on our expertise, at 1.25 µmol CO₂ m⁻² s⁻¹ for NEE and 10 W m⁻² for energy fluxes $H$ and $LE$. Fluxes corresponding to an unrotated vertical wind velocity mean $w > 0.35$ m s⁻¹ were also flagged 2, because measurements over this threshold cannot be properly corrected with rotation procedures (Foken and Wichura, 1996; Göckede et al., 2004). In the remainder of the study, filtered NEE correspond to values that pass all the filters described above and with a quality flag lower than 2.

2.3.3. Flux gapfilling and NEE partitioning between GEP and $R_n$

To compute daily to annual sums of fluxes, NEE gaps were filled in all the dataset. The algorithm described in Reichstein et al. (2005) was used for gapfilling; it was not applied to the whole dataset but on each CFP independently to account for the fast and discontinuous changes in canopy properties. After gapfilling was achieved, NEE was partitioned into gross ecosystem production (GEP) and ecosystem respiration $(R_n)$ components. The method described in Reichstein et al. (2005), based on the Lloyd and Taylor (1994) model parameters optimisation, was followed:

$$R_n = R_{ref} \cdot \exp \left( \frac{1}{T_{ref} - T_0} - \frac{1}{T_s - T_0} \right)$$

(5)

where $R_{ref}$ is the respiration at the reference temperature $T_{ref}$ (here 10 °C therefore $R_{ref} = R_{10}$), $T_0$ is a parameter describing $R_n$ sensitivity to temperature, and $T_s$ is a temperature scale parameter kept constant at −46.02 °C as in Lloyd and Taylor (1994) to avoid any over-parameterization of the model as explained by Reichstein et al. (2005). First, the model parameter $T_0$ was optimised using nocturnal filtered NEE (equal to the observed ecosystem respiration) for each CFP, because it is strongly correlated to canopy properties (see Reichstein et al. 2005) for a full description of the optimisation process. Then $R_{ref}$ was optimised with nocturnal filtered NEE for five days sliding windows with a two day step and interpolated every half-hour. Diurnal $R_n$ was then calculated using Equation 5 with optimised $T_0$ and $R_{ref}$ and diurnal $T_s$. Diurnal GEP was finally calculated as the difference between the diurnal gapfilled NEE and the diurnal calculated $R_n$.

2.3.4. Carbon balance calculation and uncertainty assessments

Net ecosystem production (NEP) was defined as the annual integration of half-hourly NEE values. NEP was computed from early October to late September, because this period generally begins after summer crop harvest and before the beginning of winter crop sowing. Therefore, this integration period is valid for both winter and summer crop species. However, in 2005, because continuous EC measurements started on 18-Mar-2005, the NEP for rapeseed at Auradé and triticale at Lamasquère were computed between 18-Mar-2005 and 17-Mar-2006. Although this integration period is not ideal because growth had already started in March, these data were integrated into the analysis because of the lack of flux data concerning triticale and rapeseed in the literature.

Three different sources of random errors were investigated to assess NEP uncertainty:

1. The uncertainty introduced in NEP by the random error of the systematic $u_*$ threshold determination $(\sigma(\text{NEP}_u))$ was assessed with the same bootstrapping approach as in Papale et al. (2006). Data were re-sampled 100 times using the bootstrap approach to determine $100 u_*$ thresholds. NEE were then filtered with the new $u_*$ thresholds $(\text{NEE}_u)$ and gapfilled. All other treatments on $\text{NEE}_u$ were the same as described in Section 2.3.2. NEP from the 100 $u_*$ thresholds $(\text{NEP}_u)$ were then computed. $(\sigma(\text{NEP}_u))$ was calculated as the standard deviation of all the NEP$_u$.

2. Random errors in measurement can also introduce uncertainties in NEP via gapfilling and data integration (Dragoni et al., 2007; Rannik et al., 2006; Richardson and Hollinger, in press). We followed the Richardson and Hollinger (in press) methodology to calculate the uncertainty introduced in NEP by the random errors in measurement $(\sigma(\text{NEP}_m))$ in the following steps:

- Random errors $(\delta)$ were calculated as the differences between fluxes in similar climatic conditions on two successive days (Richardson et al., 2006).

- A relation between $(\sigma(\delta))$ and NEE was established for 20 NEE bins with the same number of data in each bin. Both sites were included in this relation, because they have the same instrumentation set up and the same ecosystem type. The following relations were found:

$$\sigma(\delta) = 0.15(\text{NEE}) + 0.87 \quad \text{for NEE} < 0 \quad \left( R^2 = 0.82 \right)$$

$$\sigma(\delta) = -0.20(\text{NEE}) + 0.47 \quad \text{for NEE} \geq 0 \quad \left( R^2 = 0.63 \right)$$

(6a)

(6b)

- Random noise from a double exponential distribution with 0 mean and $(\sigma(\delta))$ standard deviation calculated from Equation 6a and 6b was added to filtered NEE $(\text{NEE}_f)$. $(\text{NEE}_f)$ was then gapfilled, and the noisy NEP $(\text{NEP}_g)$ was computed. This last step was repeated 100 times, and $(\sigma(\text{NEP}_g))$ was calculated as the standard deviation of all the NEP$_g$.

3. The uncertainty introduced in NEP by the gapfilling method errors $(\sigma(\text{NEPgap}))$ was analysed through a gap distribution impact analysis. First, filtered NEE were gapfilled. Then random noise from a double exponential distribution with 0 mean and $(\sigma(\delta))$ standard deviation (Eqs (6a) and (6b)) was added to the modelled NEE resulting from gapfilling procedures; no random noise was added to the filtered NEE. This procedure was done to avoid the smoothing impact of gapfilling procedures. Then gaps (same number, same size, and with approximately the same distribution between night and day as observed in filtered NEE) were randomly introduced in this gapfilled NEE $(\text{NEEgap})$. NEEgap was then gapfilled and integrated to compute NEP $(\text{NEPgap})$. Gap re-introduction and NEPgap computation was done 100 times, $(\sigma(\text{NEPgap}))$ was calculated as the standard deviation of all the NEP$_{gap}$.

Assuming a normal distribution of NEP$_u$, NEP$_g$ and NEP$_{gap}$ and that these three sources of error were independent, NEP standard deviation, $(\sigma(\text{NEP}))$, was estimated as the quadratic sum of $(\sigma(\text{NEP}_u))$, $(\sigma(\text{NEP}_g))$ and $(\sigma(\text{NEPgap}))$. NEP uncertainty was reported at a 95%
confidence interval as 2σ(NEP). Although this method is not an exhaustive description of random and systematic error associated with the EC method (for more details see Anthoni et al., 2004a; Goulden et al., 1996; Moncrieff et al., 1996), it allows estimation of NEP uncertainty in a systematic way, valid for all ecosystem type, and with the main sources of error caused by standard flux data treatments.

Carbon output through Exp and input through organic fertilization (OF) were analysed to evaluate management effects on carbon balance at the plot scale. Therefore, net biome production (NBP) was defined as:

\[ \text{NBP} = \text{NEP} + \text{OF} + \text{Exp} \]  

(7)

As in Hollinger et al. (2005), Exp was considered a rapid carbon release to the atmosphere; thus, it was positive. OF was considered a carbon input to the plot, and thus was negative. The standard deviation of \( \sigma(\text{OF}) \), was calculated from analyses of the carbon content in organic fertiliser provided by the farmer. Assuming independence and normality of the different error sources, \( \sigma(\text{NBP}) \) was calculated as the quadratic sum of \( \sigma(\text{NEP}) \), \( \sigma(\text{Exp}) \) and \( \sigma(\text{OF}) \).

2.3.5. Net ecosystem exchange (NEE) response to light

Only filtered NEE data were used for the light response analysis to avoid artificial relations between PPFD and gapfilled NEE. Relations between daytime NEE (NEE\(_d\)) and aPPFD were determined at each crop, maximum development (PAI\(_{\text{max}}\) = 0.5 ≤ PAI ≤ PAI\(_{\text{max}}\) where PAI\(_{\text{max}}\) is the maximal value of PAI) to limit crop dynamics effects on these relations. A nonrectangular hyperbolic light response model (Gilmanov et al., 2003) was fitted to each dataset:

\[ \text{NEE}_d = \frac{1}{20} \left( \alpha \cdot \text{aPPFD} + \beta \right) - \sqrt{\alpha \cdot \text{aPPFD}^2 + 4\beta \cdot \text{aPPFD}} \]  

\( \alpha \) is the initial slope of the light response curve, \( \beta \) is NEE\(_d\) at light saturation, \( \phi \) is the respiration term and \( \theta \) is the curvature parameter (0 < \( \theta \) ≤ 1). All fitted parameters and fitting statistics are reported in Table 3. Periods with high vapore pressure deficit (VPD), leading to a decrease in stomatal conductance and therefore to a decrease in NEE\(_d\), were discarded from this analysis because this phenomenon was not accounted for in Eq. (8). VPD thresholds were estimated for each crop by the analysis of the distribution of NEE residuals (NEE\(_{\text{res}}\)), computed as the difference between observed NEE and modelled NEE by Eq. (8). NEE\(_{\text{res}}\) were averaged for 1 hPa VPD bins. VPD threshold was defined as the lower VPD bin with NEE\(_{\text{res}}\) averages significantly higher than 0 (one-sample unpaired t-test, \( p \)-value < 0.05), meaning a systematic overestimation of NEE\(_d\) by the model beyond this threshold.

NEE\(_{\text{res}}\) were also analysed against aPPFD, soil water content (SWC) and \( T_a \) (data not shown). For aPPFD and SWC, NEE\(_{\text{res}}\) were randomly distributed around 0 with no clear pattern. These results indicate a satisfying NEE\(_{\text{res}}\) representation by Eq. (8) and show that no evident water stress was observed for any crop at maximum development. At high \( T_a \) modelled NEE\(_{\text{res}}\) overestimations were observed; however, a strong correlation between VPD and \( T_a \) (R\(^2\) = 0.78 on average for the 6 datasets) leads us to think that this observation is mostly due to VPD.

3. Results and discussion

3.1. Site meteorology

Annual climatic means from our two stations were compared to climatic normals (30 year average) recorded at the “Toulouse Blagnac” Meteo France station located 22 and 14 km from the Auradé and Lamasqué plots, respectively (Table 1). On an annual basis, no climatic anomalies were observed for both sites, with mean annual temperature and precipitation close to normals; except during the 2007 cropping season, where mean annual temperature was slightly warmer than normals, and less precipitation was observed at the Lamasqué site than normals. For the 3 cropping seasons, temperature, precipitation and wind speed were slightly lower at Lamasqué than at the Auradé plot, but trends were very similar (Fig. 1). On a quarterly basis, except for large precipitations observed in spring 2007, seasonal precipitation dynamics were not well-marked. Precipitation was generally similar on both sites but with strong local differences caused by thunderstorm events (Fig. 1d). On a weekly basis, no major differences were observed for PPFD and \( T_a \) between the two sites. During the winter of 2006–2007, episodes with high elevated \( T_a \) were observed on both sites compared to the winter of 2005–2006. Main wind directions were similar at the two sites, but more scatter was observed at Lamasqué (Table 1). SWC in the first 30 cm of soil followed globally the same evolution for both sites except during 2006 summer because of irrigation at Lamasqué (Fig. 1c and d). Absolute values of SWC were higher at Lamasqué than at Auradé, most likely because of a larger retention capacity at the soil at Lamasqué due to higher clay content (Table 1) and (2). The proximity of the “Touch” river at Lamasqué, therefore, this absolute difference did not necessarily induce a difference in soil water availability for plants.

3.2. Crop growth and production

For winter crops (rapeseed, triticale and winter wheat), growth started with germination in November and remained slow until March (Figs. 2 and 3). However, winter wheat growth in 2007 at Lamasqué started earlier than for the other winter crops due, almost certainly, to the high temperature episodes during winter 2006–2007 (Fig. 1). The same phenomenon was observed by Aubinet et al. (submitted for publication) for 2007 winter wheat at the Lonnée site in Belgium. Maximum growth was observed from late April to late May. PAI\(_{\text{max}}\) (Table 2) and the maximum leaf biomass were reached between the end of April and the middle of May, followed by senescence. For rapeseed, total biomass corresponded to leaves until April but all leaves had fallen by early June, even if the stems were still photosynthetically active. During senescence, biomass was reallocated from leaves and stems to fruits (Fig. 3). For summer crops (maize and sunflower), growth started in late May. Aboveground biomass increase was relatively constant until the beginning of August for sunflower and the beginning of September for maize. For both summer crops, PAI was at its maximum in the middle of July (Fig. 2, Table 2). Maize was harvested early at the end of August, corresponding to the beginning of senescence, because it was used for silaging. For both winter and summer crops, PAI is a more relevant indicator of photosynthetic area than LAI because leaves are not the only photosynthetic organ. This was particularly true at the end of rapeseed development in early June 2005, with PAI values higher than 1.5 m\(^2\) m\(^{-2}\) and GEP values lower than –8 g C m\(^{-2}\) d\(^{-1}\) even though LAI values were close to 0 m\(^2\) m\(^{-2}\) as explained above (Figs. 2 and 4). AGB ranged from 324 ± 157 g C m\(^{-2}\) for Auradé sunflower in 2007 to 810 ± 311 g C m\(^{-2}\) for Lamasqué maize in 2006 (Table 2). On average, AGB were 36% lower at Auradé than at Lamasqué, but Exp were 65% lower at Auradé than at Lamasqué. This more important difference in Exp is linked to crop residues, which were 1.9 times higher at Auradé than at Lamasqué. This is...
because Lamasquère is a cattle breeding farm exporting most of the aboveground biomass for cattle bedding and feeding, whereas Auradé is a cereal production farm exporting only the seeds. Residues were particularly low for maize in 2006 at Lamasquère because all aboveground biomass was used for silaging.

3.3. Seasonal changes in carbon fluxes

Net carbon fluxes over crop ecosystems are influenced by different processes; some are natural (photosynthesis and respiration), and others are caused by human activities (organic fertilization, tillage, ...). Fig. 4 presents the evolution of gross ecosystem production (GEP, i.e., ecosystem carbon uptake by both crop and weed photosynthesis) and ecosystem respiration (\( R_E \); i.e., autotrophic and heterotrophic respiration). In order to separate the impacts of temperature from the other possible \( R_E \) driving variables (phenology, growth, water, management, etc.) the normalized ecosystem respiration at a reference temperature of 10 °C \( (R_{10}) \) is also reported in Fig. 4.

3.3.1. Gross ecosystem production (GEP)

The dynamics of GEP of the different crops were close to those of PAI (Figs. 2 and 4). For winter crops, GEP remained low like PAI until March, except for winter wheat in 2007 at Lamasquère. Indeed, winter wheat development occurred earlier in winter 2006–2007 because of the warm episodes described above. Therefore, absolute GEP values were high from December to March compared with winter wheat at Auradé in 2006. Overall, during crop development, absolute values of GEP increased to a maximum value \( (\text{GEP}_{\text{max}}) \) corresponding to \( \text{PAI}_{\text{max}} \). Daily carbon fluxes at maximum crop development are reported in Table 2 for each crop. For winter crops, GEP\(_{\text{max}}\) ranged between \(-15.4 \text{ g C m}^{-2} \text{ d}^{-1}\) for rapeseed reached on 24-May-2005 at Auradé and \(-18.9 \text{ g C m}^{-2} \text{ d}^{-1}\) for winter wheat reached on 21-Apr-2007 at Lamasquère. These estimates agree with the measured values.
with those reported over other winter wheat crops, 
-17.4 g C m⁻² d⁻¹ and -16.4 g C m⁻² d⁻¹ for the Ponca (USA) 
and Soroe (Denmark) sites, respectively (Falge et al., 2002),
about -16 g C m⁻² d⁻¹ at the Gebesee (Germany) site (Anthoni
et al., 2004a) and -15 g C m⁻² d⁻¹ at the Lonzeé (Belgium) site
(Aubinet et al., submitted for publication). For maize, GEP_max
was -19.6 g C m⁻² d⁻¹. Suyker et al. (2005) reported higher
absolute GEP values of about -27 g C m⁻² d⁻¹. However, GEP_max
per leaf area unit were higher at our site than in Suyker et al.
(2005), with respective values of 5.8 g C m⁻² leaves d⁻¹ (maximum
LAI = 3.4 m² m⁻²) and 4.5 g C m⁻² leaves d⁻¹ (maximum
LAI = 6 m² m⁻²). The low GEP_max observed at our site was
probably not caused by physiological stress but by low LAI
values. Moreover, the high GEP_max per leaf area unit observed at
our site could be interpreted as higher light use by the
photosynthetic tissues caused by lower shadow effects at lower
LAI. The difference in LAI can be explained by differences in
irrigation. At our site, the irrigation amount was two times
lower than in Suyker et al. (2005) (precipitation + irrigation
during vegetation period were respectively 413 and 749 mm).
Verma et al. (2005) reported maximum LAI values of 3.9 m² m⁻²
over rainfed maize with precipitation of 433 mm during the
vegetation period, which is comparable to our study. Differences
in maize variety (grain production in Suyker et al. (2005) and
silaging at our site) and associated management practices might
also explain LAI differences. Sunflower had the lowest absolute
GEP max rate of -13.7 g C m⁻² d⁻¹, probably because of the lower
PAI of this crop (PAI_max = 2 m² m⁻²) compared to the others.
Then crops entered into senescence, and the absolute values of
GEP decreased until harvest. For maize, the interruption in
carbon assimilation was sudden due to an early harvest just
after the beginning of senescence. This event occurred so that
the maize was used for silaging.
After harvest (see Section 2.1 and Fig. 5 for dates), absolute
values of GEP often increased again due to the re-growth of
seeds that fell during harvest and the growth of weeds under

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favourable meteorological conditions. A long re-growth period was observed at Lamasque`re after the triticale harvest in 2005, with PAI values of about 0.7 m$^2$/m$^2$ (estimated with hemispherical photography) and GEP values reaching -5.65 g C m$^{-2}$ d$^{-1}$ on 22-Oct-2005. Two other re-growth events occurred at Auradé at the end of summer and in fall 2005 with absolute GEP values smaller than for the Lamasque`re re-growth. Re-growth was more important after 2005 crops than after 2006 crops.

Table 2
Values at the maximum of crop development of plant area index (PAI$_{\text{max}}$), daily ecosystem respiration (RE$_{\text{max}}$) and gross ecosystem production (GEP$_{\text{max}}$). Carbon content in the aboveground biomass (AGB) just before harvest, and in residue biomass and exported biomass (Exp) just after harvest were also reported. Values after the symbol $\pm$ are the standard deviations from the mean.

<table>
<thead>
<tr>
<th>Sites</th>
<th>PAI$_{\text{max}}$ (m$^2$/m$^2$)</th>
<th>RE$_{\text{max}}$ [g C m$^{-2}$ d$^{-1}$]</th>
<th>GEP$_{\text{max}}$ [g C m$^{-2}$ d$^{-1}$]</th>
<th>AGB [g C m$^{-2}$]</th>
<th>Residues [g C m$^{-2}$]</th>
<th>Exp [g C m$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auradé 2005</td>
<td>3.4 $\pm$ 0.6</td>
<td>8.0</td>
<td>-15.4</td>
<td>482 $\pm$ 158</td>
<td>269 $\pm$ 76</td>
<td>213 $\pm$ 61</td>
</tr>
<tr>
<td>Winter wheat 2006</td>
<td>3.8 $\pm$ 1.3</td>
<td>7.0</td>
<td>-15.6</td>
<td>516 $\pm$ 115</td>
<td>237 $\pm$ 66</td>
<td>279 $\pm$ 42</td>
</tr>
<tr>
<td>Sunflower 2007</td>
<td>2.0 $\pm$ 1</td>
<td>7.3</td>
<td>-13.7</td>
<td>324 $\pm$ 157</td>
<td>220 $\pm$ 67</td>
<td>104 $\pm$ 36</td>
</tr>
<tr>
<td>Lamasque`re</td>
<td>3.9 $\pm$ 1.2</td>
<td>7.0</td>
<td>-17.1</td>
<td>663 $\pm$ 109</td>
<td>158 $\pm$ 41</td>
<td>505 $\pm$ 39</td>
</tr>
<tr>
<td>Triticale 2005</td>
<td>3.6 $\pm$ 0.8</td>
<td>11.0</td>
<td>-19.6</td>
<td>810 $\pm$ 311</td>
<td>4 $\pm$ 3</td>
<td>806 $\pm$ 57</td>
</tr>
<tr>
<td>Maize 2006</td>
<td>5.4 $\pm$ 1.5</td>
<td>11.5</td>
<td>-18.9</td>
<td>600 $\pm$ 125</td>
<td>213 $\pm$ 82</td>
<td>386 $\pm$ 47</td>
</tr>
<tr>
<td>Winter wheat 2007</td>
<td>5.4 $\pm$ 1.5</td>
<td>11.5</td>
<td>-18.9</td>
<td>600 $\pm$ 125</td>
<td>213 $\pm$ 82</td>
<td>386 $\pm$ 47</td>
</tr>
</tbody>
</table>
and 2007 crops because of important rainfall events and high temperatures in Fall 2005 (Fig. 1). After maize and sunflower crops, the stubbles were ploughed into the soil, and winter wheat was seeded; therefore, no re-growth was observed. For the other crops, re-growth was stopped by the different tillage operations (see Section 2.1 for dates). Low absolute GEP values during winter were caused by (1) low temperatures that reduced ecosystem activity for winter crops and (2) absence of vegetation during the winter and spring preceding the summer crop.

3.3.2. Ecosystem respiration \((R_E)\)

\(R_E\) and \(R_{10}\) seasonal dynamics were quite similar. This suggests that, at a seasonal scale, crop development is a more important driving variable for \(R_E\) than temperature. This hypothesis is confirmed by measurements at our sites showing that autotrophic respiration represents the largest proportion of \(R_E\) during vegetation periods (Sagnier and Le Dantec, personal communication). \(R_{10}\) and \(R_E\) evolution differed more for summer crops probably because of high summer temperature affecting \(R_E\). \(R_E\) globally followed the same dynamics as GEP and PAI during crop development. However, in spring 2005, \(R_E\) was delayed compared to GEP. A sudden \(R_E\) increase occurred in late April, whereas absolute GEP had already increased. Lags between GEP and \(R_E\) dynamics have already been observed by Falge et al. (2002) in temperate deciduous and boreal coniferous forests. Both phenological and climatic factors could explain this lag. Heading and flower emergence are known to induce an increase in crop respiration (Baldocchi, 1994), and the late \(R_E\) increase occurred at this phenological stage. However, as \(R_E\) delay was not visible for 2006 and 2007 winter crops, this reinforces the fact that phenology was not the only factor. Low temperatures until late April followed by a rapid temperature increase and 45 mm of rainfall between 20–April-2005 and 01-May-2005 (Fig. 1) could have induced a sudden \(R_E\) increase. These two meteorological events can contribute to soil micro-organism activation and quickening of crop development. Maximum \(R_E\) values \((R_{E_max})\) for winter crops ranged between 7.0 g C m\(^{-2}\) d\(^{-1}\) on 17-May-2006 for winter wheat at Auradé and 11.5 g C m\(^{-2}\) d\(^{-1}\) on 24-Apr-2007 for winter wheat at Lamasquère. These observed values are higher than those reported in Falge et al. (2002) over two winter wheat plots (3.1 g C m\(^{-2}\) d\(^{-1}\) and 5.6 g C m\(^{-2}\) d\(^{-1}\)), but agree with values of 8 g C m\(^{-2}\) d\(^{-1}\) reported by AUBINET et al. (submitted for publication) over a winter wheat crop. As \(GEP_{max} R_{E_{max}}\) estimated over maize in the present study was lower than the one (13 g C m\(^{-2}\) d\(^{-1}\)) reported by Suyker et al. (2005), because of the LAI difference explained above.

During intercropping periods, \(R_E\) was relatively low at both sites, but peaks occurred. As these peaks affected both \(R_E\) and \(R_{10}\), they were not controlled by temperature. Generally rainfall events, ploughing, residue incorporation into the soil and re-growth could explain these peaks. For example, \(R_E\) and \(R_{10}\) increased in the beginning of August 2005 at Auradé, which occurred following incorporation of residues and plant re-growth into the soil by the cover crop on 04-Aug-2005 and a 55 mm rainfall event between 10-Aug-2005 and 11-Aug-2005. In the absence of vegetation on the plot at this time, this \(R_E\) increase could be explained by micro-organism activation caused by higher water and substrate availability for decom-
position. Generally, high RE rates in summer after harvest in 2005 for both sites and in 2006 at Auradé were mainly caused by re-growth and soil water availability (Figs. 1 and 4).

3.3.3. Net ecosystem exchange (NEE) and carbon storage dynamics

NEE dynamics allow the determination of GEP and RE importance in the ecosystem carbon dynamics, whereas cumulated NEE allows the identification of carbon storage or release periods (Fig. 5). A negative slope on the cumulated NEE curve means that the ecosystem behaves as a carbon sink (GEP > RE), and a positive slope means that the ecosystem behaves as a carbon source (GEP < RE). Overall, the dynamics were well-marked with alternating carbon sequestration and carbon release periods corresponding to crop growth and bare soil, respectively. For the three observed seasons, Lamasquère was a stronger carbon sink than Auradé without considering management effects (see Section 3.5.2).

Development of crops (denoted C) appeared quite different for winter and summer crops. For winter wheat, NEE values were close to 0 g C m\(^{-2}\) d\(^{-1}\) (GEP = RE) from the beginning of November until February at Auradé in 2006 and only until December at Lamasquère in 2007. Then, for all winter crops, NEE values became negative, and the ecosystem stored carbon until the beginning of June. Maximum absolute NEE values of −8.6, −9.7, −10.5 and −9.8 g C m\(^{-2}\) d\(^{-1}\) were observed at Auradé for rapeseed and winter wheat and at Lamasquère for triticale and winter wheat, respectively. Between May and June, GEP decreased because senescence began, although RE remained high; therefore, carbon storage became less important with decreasing absolute NEE values. In June, senescence was observed with a fast change in the sign of NEE, which became positive because RE values became higher than absolute GEP values. For summer crops (maize and sunflower), NEE values were positive until June, about one and a half months after sowing. The NEE became negative and maximum absolute NEE values of −7.8 and −10.2 g C m\(^{-2}\) d\(^{-1}\) were observed at Auradé for sunflower and at Lamasquère for maize, respectively. The ecosystem stored carbon from June to August for sunflower and from mid-June to harvest (denoted H) for maize. The reversal from a carbon sink to a carbon source was more progressive for sunflower than for winter crops because of a slower senescence. For maize, the inversion was sudden because it was harvested, whereas it was still green just after the beginning of senescence.

Re-growth events (denoted R) after harvest had visible effects on NEE and cumulated NEE. NEE decreased progressively, and occasionally negative NEE values were observed at Auradé in 2005 and 2006. During the 2005 re-growth event, the slope of cumulated NEE was close to 0. Photosynthesis balanced soil and vegetation respiration during periods when only carbon losses from soil respiration should have occurred. The re-growth effect was even more important at Lamasquère because the ecosystem switched

![Fig. 5. Daily net ecosystem exchange (NEE) evolution (left axis) and cumulated values of NEE (right axis) from 18-Mar-2005 to 01-Oct-2007 at the Auradé (a) and Lamasquère (b) plots. Crop development (denoted as C) and re-growth (denoted as R) periods were reported at the top of each subplot. Annotations corresponding to vertical dotted lines give information about punctual management operations affecting NEE: S is crop sowing, H is harvest and T and P are superficial tillage and deep ploughing, respectively.](https://example.com/fig5.png)
from a source to a sink. Negative NEE values down to −2 g C m⁻² d⁻¹ were observed during re-growth events in 2005, and it allowed a net carbon storage of −57 g C m⁻².

Tillage (denoted T for superficial tillage and P for deep ploughing) affected the cumulated NEE in two ways, as described in Sections 3.3.1 and 3.3.2: (1) it stopped carbon assimilation from re-growth events, and (2) it could contribute to important soil respiration increases when associated with rainfall events and incorporation of plant residues as on 10-Aug-2005 at Auradé.

Tillages before summer crops at Auradé and Lamasquère and the non-inverting tillage between maize and winter wheat at Lamasquère had no visible impact on NEE.

3.4. NEE response to light

Ecosystem net carbon fluxes of the different crops were compared in terms of response to light in order to evaluate the influence of climatic variables, species and sites on NEE as well as annual carbon balance.

3.4.1. Climatic control on NEE response to light

The VPD threshold above which NEE modelled by Eq. (8) were overestimated (see Section 2.3.5) was on average 27% lower for winter crops than for summer crops (Table 3). This shows that summer crops are more adapted to high VPD than winter crops; their higher stomatal conductance was underlined by their higher net carbon fixation rate at high VPD.

Except for rapeseed at Auradé in 2005, the datasets were split into two parts according to light quality. The first one corresponded to the ratio of diffuse PPFD to total PPFD (d/1) lower than 0.5 (clear sky conditions) and the other to d/1 higher than 0.5 (cloudy conditions).

It can be seen that for aPPFD above 400 μmol m⁻² s⁻¹, NEE values were higher for diffuse conditions (Fig. 6). Such observations have already been reported for many ecosystems (Alton et al., 2007; Gu et al., 2002; Law et al., 2002; Moureaux et al., 2006; Suyker et al., 2004). Considering all crops except rapeseed, the mean β and α were higher (−51 μmol CO₂ m⁻² s⁻¹ and −0.051 mol mol⁻¹, respectively) in diffuse light conditions than in direct light conditions (−33 μmol CO₂ m⁻² s⁻¹ and −0.028 mol mol⁻¹). Large differences in parameterisation between diffuse and direct conditions were also observed by Gu et al. (2002) on different ecosystems (Scots pine forest, aspen forest, tallgrass prairie, mixed forest and wheat crops). Higher values of β and α for diffuse light conditions were probably caused mainly by the limitation of shadow effects with a more homogeneous distribution of radiation among all leaves in plant canopies (Gu et al., 2002). It induced better light use efficiency for NEE and limited saturation effects.

The determination coefficient (R²) and the root mean square error (RMSE) were respectively 35% higher and 37% lower for cloudy conditions than for clear sky conditions. It was probably because aPPFD were usually higher for clear sky conditions, and this corresponds to the saturation part of the global light response curve. Therefore, aPPFD was probably not the most important driving variable influencing NEEd during clear sky conditions (Baldocchi, 1994); indeed, air and soil temperature, humidity, wind speed and measurement error are more important driving variables of NEEd in clear sky conditions.

3.4.2. Species and site impact on NEE response to light

Comparison of crop behaviours and fitting parameters in both clear sky and cloudy conditions (Fig. 6 and Table 3) shows that light saturation seems to be correlated to PAImax values (Table 2).

Indeed, low β as observed for sunflower at Auradé in 2007, correspond to low PAImax while high β as observed for winter wheat at Lamasquère in 2007, correspond to high PAImax. With similar aPPFD values in both cases, the lower the PAI is, the more
light can easily penetrate deeply within the canopy, and the more light saturation can occur rapidly. Leaf orientation, which is planophile for sunflower (and almost erectophile for winter wheat), may also contribute to the earlier saturation of the crop at high solar incident angles due to more important shadows effects. This phenomenon also affected $\alpha_c$, which was 60% lower for sunflower than for Lamasque 2007 winter wheat. For all other crops, PAI max were similar (3.4 m$^2$ m$^{-2}$ < PAI max < 3.9 m$^2$ m$^{-2}$). It is noteworthy that no marked differences in $\alpha_a$ and $\beta_a$ were observed between C3 winter crops (rapeseed, winter wheat and triticale) and the C4 summer crop (maize). Indeed, Baldocchi (1994) observed lower $\alpha$ values for maize than for winter wheat crop, but it was caused by lower PPDF absorbed by the maize canopy on their sites. In our case, aPPFD values were similar for both C3 winter crops and maize. This can be explained by: (1) $K_a$ values being higher for maize than for C3 winter crops, resulting in a lower light use efficiency for maize at our site, as it was noted by Ruimy et al. (1995), (2) canopy architecture, as mentioned above, being more erectophile for winter wheat and triticale than for maize, (3) footprint mismatching between the flux measurements and PAI and aPPFD measurements and (4) limitations of NEE description quality by Eq. (8). Other factors, such as soil type, fertilization supply and inter-annual climate variability, could contribute to observed differences in crop carbon assimilation efficiency between sites and species, but they are difficult to assess here.

3.5. Crop carbon balance

3.5.1. Annual net ecosystem production (NEP)

For winter crops, NEP ranged from $-286 \pm 23$ g C m$^{-2}$ y$^{-1}$ for rapeseed in 2005 at Auradé to $-369 \pm 33$ g C m$^{-2}$ y$^{-1}$ for winter wheat.
### Table 4
Annual net ecosystem production (NEP) at different crop sites and for different crop species.

<table>
<thead>
<tr>
<th>Crop species</th>
<th>NEP, (g C m⁻² y⁻¹)</th>
<th>Site/Year</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer crops</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainfed maize (mean value)</td>
<td>-454</td>
<td>Mead 2001, 2002</td>
<td>Verma et al. (2005)</td>
</tr>
<tr>
<td>Irrigated maize (mean value)</td>
<td>-480</td>
<td>Mead 2001–2003</td>
<td>Verma et al. (2005)</td>
</tr>
<tr>
<td>Maize (conventional and reduce tillage)</td>
<td>-290 to –300</td>
<td>Rosemont 2003</td>
<td>Baker and Griffis (2005)</td>
</tr>
<tr>
<td>Maize</td>
<td>-186 ± 42</td>
<td>Gebesee 2002</td>
<td>This study</td>
</tr>
<tr>
<td>Potato</td>
<td>-49 to 29</td>
<td>Lamassquère 2006</td>
<td>Anthoni et al. (2004b)</td>
</tr>
<tr>
<td>Soybean (conventional and reduce tillage)</td>
<td>-50 to –85</td>
<td>Rosemont 2002</td>
<td>Baker and Griffis (2005)</td>
</tr>
<tr>
<td>Soybean (mean value)</td>
<td>18 to 48</td>
<td>Mead 2002</td>
<td>Verma et al. (2005)</td>
</tr>
<tr>
<td>Spring barley</td>
<td>210</td>
<td>Jokioinen 2001</td>
<td>Lohila et al. (2004)</td>
</tr>
<tr>
<td>Sugar beet</td>
<td>-610</td>
<td>Lonzé 2004</td>
<td>Moureaux et al. (2006)</td>
</tr>
<tr>
<td>Sunflower</td>
<td>28 ± 18</td>
<td>Auradé 2007</td>
<td>This study</td>
</tr>
<tr>
<td>Winter crops</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rapeseed</td>
<td>-286 ± 23</td>
<td>Auradé 2005</td>
<td>This study</td>
</tr>
<tr>
<td>Triticale</td>
<td>-335 ± 42</td>
<td>Lamassquère 2005</td>
<td>This study</td>
</tr>
<tr>
<td>Winter wheat</td>
<td>-183</td>
<td>Ponca 1997</td>
<td>Falge et al. (2001)</td>
</tr>
<tr>
<td>Winter wheat</td>
<td>-185 to –245</td>
<td>Gebesee 2001</td>
<td>Anthoni et al. (2004a)</td>
</tr>
<tr>
<td>Winter wheat</td>
<td>-324 ± 20</td>
<td>Auradé 2006</td>
<td>This study</td>
</tr>
<tr>
<td>Winter wheat</td>
<td>-369 ± 33</td>
<td>Lamassquère 2007</td>
<td>This study</td>
</tr>
<tr>
<td>One year rotation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winter wheat * maize</td>
<td>-197.6</td>
<td>Yucheng 2003</td>
<td>Jun et al. (2006)</td>
</tr>
<tr>
<td>Winter wheat * maize</td>
<td>-317.9</td>
<td>Yucheng 2004</td>
<td>Jun et al. (2006)</td>
</tr>
</tbody>
</table>

852 wheat in 2007 at Lamassquére (Table 4). Despite its large annual GEP, maize NEP was only –186 ± 42 g C m⁻² y⁻¹. The ratio of annual GEP to annual GEP denoted \( \frac{\text{NEP}}{\text{GEP}} \) allows the determination of the respective contribution of crop carbon assimilation by photosynthesis and ecosystem respiration to NEP. The stronger sink of carbon was observed at the Lonzé sugar beet crop in Belgium (Moureaux et al., 2006) and the stronger source at the Jokioinen spring barley crop in Finland (Lohila et al., 2004). For the Chinese site of Yucheng (Jun et al., 2006), carbon storage seemed a bit uncertain because of differences in dates concerning the beginning and the end of the period used for annual NEP calculation, which were sometimes not explicitly reported. It is therefore important to normalize and specify it for future NEP-inter-comparisons exercises.

NEP uncertainty (2σ/NEP) estimated in the present study ranged between ±18 g C m⁻² y⁻¹ for sunflower at Auradé and ±42 g C m⁻² y⁻¹ for triticale and maize at Lamassquère. This estimation of NEP uncertainty is in the same range of values as those reported in the Baldocchi (2003) review over different sites. In that study, NEP uncertainty ranged from ±30 g C m⁻² y⁻¹ at Harvard forest to ±68 g C m⁻² y⁻¹ for a short bog with different estimations methods. Dragoni et al. (2007) calculated an uncertainty in NEP caused by measurements’ random error that varied between ±25 and ±44 g C m⁻² y⁻¹ at our sites. Richardson and Hollinger (in press) used a similar approach than in the present study to estimate NEP uncertainty due to measurements random error and to long gaps in the data set. These authors found results very close to our global uncertainty estimate, ranging between ±25 and ±44 g C m⁻² y⁻¹ at different forest sites. Independent of the method used, NEP uncertainty estimates seem relatively stable across different sites.

Table 5 reports the impacts of methodology on NEP calculation. Differences in NEP were very limited and were always in the
uncertainty range. However, NEP calculated with the conventional steady state test were systematically higher than those calculated with our modified steady state test. As it is explained in Section 2.3.2, the conventional steady state test might failed when NEE is close to 0 for mathematical reasons. Therefore, when considering bare soil periods with a low respiration rate, NEE close to 0 were discarded and replaced by gapfilled data from higher positive NEE values. It resulted in a systematic overestimation of NEP. The effect of applying fixed periods of 90 days (Reichstein et al., 2005) instead of CFP for the determination of $u^*$ threshold and gapfilling procedures is not obvious. In most cases, using 90-day periods resulted in a slight underestimation of NEP. The most critical management event that modified roughly instantaneous carbon fluxes were harvest and tillage operations. Thus, the impact on NEP should therefore depend on how the CFP and 90-day periods mismatch. Impact of $F_{cs}$ calculation from one point measurement of CO$_2$ concentration is only noticeable for 2007 NEP at Auradé and Lamasquère. Grey bars represent net ecosystem production (NEP), black bars are organic fertilization (OF), white bars are carbon output of the plot by exported biomass (Exp) and hatched bars are net biome production (NBP), i.e., the sum of NEP, OF and Exp. Of data given by the farmer, only carried out at Lamasquère (b, c and f). Vertical full lines (error bars) are the standard deviation of each variable.

Table 5
Methodology impacts on net ecosystem production (NEP). NEP was calculated with the methodology describe in the present study (see Section 2.3 for methodology details), with the application of a conventional steady state test with no absolute threshold (A), with fixed periods of 90 days that affect both $u^*$ threshold detection and gapfilling (B), with a calculation of the storage term ($F_{cs}$) from one point of the CO$_2$ concentration measurement (C) and with the simultaneous application of A, B and C. Units are g C m$^{-2}$ y$^{-1}$.

<table>
<thead>
<tr>
<th>Site/Year</th>
<th>This study</th>
<th>A: fixed 90-day periods</th>
<th>B: conventional stationarity</th>
<th>C: $F_{cs}$ from 1 point</th>
<th>A + B + C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auradé</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>-286 ± 22</td>
<td>-295 ± 22</td>
<td>-277 ± 21</td>
<td>-286 ± 22</td>
<td>-287 ± 22</td>
</tr>
<tr>
<td>2007</td>
<td>28 ± 18</td>
<td>24 ± 18</td>
<td>36 ± 19</td>
<td>31 ± 20</td>
<td>33 ± 19</td>
</tr>
<tr>
<td>Lamasquère</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>-335 ± 42</td>
<td>-352 ± 29</td>
<td>-331 ± 41</td>
<td>-335 ± 42</td>
<td>-342 ± 28</td>
</tr>
<tr>
<td>2006</td>
<td>-186 ± 42</td>
<td>-204 ± 34</td>
<td>-182 ± 36</td>
<td>-194 ± 37</td>
<td>-192 ± 30</td>
</tr>
<tr>
<td>2007</td>
<td>-369 ± 33</td>
<td>-389 ± 27</td>
<td>-362 ± 36</td>
<td>-375 ± 33</td>
<td>-381 ± 27</td>
</tr>
</tbody>
</table>

Fig. 7. The annual carbon balance at the plot scale. (a), (c) and (e) are rapeseed, winter wheat and sunflower at Auradé, and (b), (d) and (f) are triticale, maize and winter wheat at Lamasquère. Grey bars represent net ecosystem production (NEP), black bars are organic fertilization (OF), white bars are carbon output of the plot by exported biomass (Exp) and hatched bars are net biome production (NBP), i.e., the sum of NEP, OF and Exp. Of data given by the farmer, only carried out at Lamasquère (b, c and f). Vertical full lines (error bars) are the standard deviation of each variable.

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for 2006 and 2007 NEP at Lamasquère when CO₂ concentration profile was installed. In theory, as gaps in filtered NEE occurred mostly at night (53% of gap on average for both sites) when $F_{NO}$ is important, calculation of $F_{NO}$ from one point should result in an understimation of NEP. Mean diurnal variation of half-hourly $F_{NO}$ data was 2.6 times higher at Lamasquère than at Auradé (not shown). At Auradé $F_{NO}$ was relatively low because of the slight slope at this site, which may induce horizontal advection during low turbulence conditions. Thus, a slight NEP underestimation was observed at Lamasquère in 2006 and 2007 but not at Auradé in 2007. Finally, the compensation phenomenon when applying the conventional steady state test, fixed 90-day periods and $F_{NO}$ calculation from one point all together resulted in no significant differences in NEP.

3.5.2. Management impacts on annual carbon balance

For the six crops, annual NBP ranged from a significant carbon sink of $-161 \pm 66 \text{ g C m}^{-2} \text{ y}^{-1}$ for winter wheat at Lamasquère in 2007 to a strong carbon source of $372 \pm 78 \text{ g C m}^{-2} \text{ y}^{-1}$ for maize at Lamasquère in 2006 (Fig. 7). Marked differences in NBP were observed between the two crop sites, Auradé and Lamasquère. First, OF at Lamasquère was an important carbon input ranging from $-68 \pm 31$ to $-249 \pm 49 \text{ g C m}^{-2} \text{ y}^{-1}$. As a consequence, carbon inputs (NBP + OF) at Lamasquère were 58% lower than at Auradé, whereas NEP were only 35% lower. However, Lamasquère ecosystem was a carbon source. Moreover, carbon inputs through organic fertilizers and carbon outputs (NEP + OF) at Lamasquère were on average 58% lower at Auradé than at Lamasquère, meaning that the plot was a carbon sink only at Lamasquère in 2007, and 28 $\pm 2 \text{ g C m}^{-2} \text{ y}^{-1}$ for maize in Auradé in 2005 and 2006 (residues was more than 2 times higher in 2007 than the mean of 2005 and 2006). However, the ratio of $-NEP$ to $-Exp$ was equal to 0.96 for winter wheat at Lamasquère in 2007, meaning that the plot was a carbon sink only because of OF. For 2005 and 2006 crops, the ratio of $-NEP$ to $-Exp$ was 1.34 and 1.16 for rapeseed and winter wheat at Auradé, respectively, and 0.66 and 0.23 for triticale and maize at Lamasquère, respectively.

This reveals the strong impact of biomass exportation on NBP for these 2 years.

In the USA, it has been shown that maize/soybean rotation had closer to neutrality: some studies found non-significant low carbon sinks (Baker and Griggs, 2005; Dobermann et al., 2006; Hollinger et al., 2005, 2006), and others non-significant low carbon sources (Grant et al., 2007; Verma et al., 2005). These differences were mostly due to management practices (irrigation, tillage, ...). These results are comparable to those found at Auradé with a carbon balance for the 3 years close to neutrality. At Lamasquère, the mean NBP for the 3 years was about 100 $\text{ g C m}^{-2} \text{ y}^{-1}$; therefore, this site is a carbon source. Similar observations have been made in other agrosystems. Anthoney et al. (2004a) found that winter wheat crop was a significant carbon source with a NBP between 45 and 105 $\text{ g C m}^{-2} \text{ y}^{-1}$. Similar carbon sources were reported in north China by Jun et al. (2006) over 2 one-year winter wheat/maize rotations with NBP between 108 and 341 $\text{ g C m}^{-2} \text{ y}^{-1}$. For a four years rotation of sugar beet/winter wheat/potato/winter wheat, Aubinet et al. (submitted for publication) observed a slightly mean NBP of 42 $\text{ g C m}^{-2} \text{ y}^{-1}$. However, they concluded that the large climatic difference in 2007 led to an underestimation of NBP; therefore, they computed a NBP of 90 $\text{ g C m}^{-2} \text{ y}^{-1}$ by substituting 2007 data with 2005 data. Grant et al. (2007) confirmed all these results for NBP by a modelling approach over 100 years, showing that carbon storage potential in agro-ecosystem soils is limited.

In the present study, larger uncertainties were observed for NBP than for NEP, and they were mostly due to important uncertainties in Exp and in OF. Therefore, we recommended that careful biomass sampling and regular OF analysis should be done to limit these uncertainties, even if these manipulations are very fastidious and time consuming.

4. Summary and conclusions

Carbon fluxes and the carbon balance of a succession of three crops were analysed at two cropland sites in South West France using the EC method and biomass sampling. With special care concerning the method of flux computation and correction adapted for croplands, NEE was partitioned into GEP and $R$, and integrated over the year to compute NEP and NBP. We observed that the carbon flux dynamics were strongly correlated to crop development at the two sites. Winter crops had an earlier and a longer vegetation period than summer crops. However, inter-annual climate variability affected these dynamics. For example, winter wheat at Lamasquère in 2007 had an elevated winter development caused by exceptionally warm conditions. Another factor that had a strong impact on carbon fluxes was management practices. We observed that re-growth events could limit the carbon release of the ecosystem by introducing negative NEE values during periods when respiration should be the only cause of carbon fluxes. Tillage limited carbon storage, avoiding re-growth and, if associated with rainfalls, it increased $R_c$ by supplying substrate and enhancing micro-organism decomposition activity. Without these conditions, tillage effects on carbon fluxes were less obvious at our sites. NEE light response curves revealed differences in crops carbon assimilation. Both climatic (light intensity and quality, VPD, etc.) and plant species (PAL, plant architectures, physiology, etc.) variables affected this response in different ways and therefore introduced differences in NEP and NBP. Moreover, these variables can be correlated to and affected by management practices like fertilization and by site specificities.

NEP ranged between $-369 \pm 33 \text{ g C m}^{-2} \text{ y}^{-1}$ for winter wheat at Lamasquère in 2007 and $28 \pm 18 \text{ g C m}^{-2} \text{ y}^{-1}$ for sunflower at Auradé in 2007. Higher absolute NEP values for winter crops than for summer crops were observed, due to the longer season length for carbon assimilation. Differences between winter or summer crops were thought to be due mostly to year to year climate variability and differences in crop species. At the annual scale, we showed that the methodology impact on NEP was less than our uncertainty estimations; however, using the conventional stationarity test without an absolute threshold could lead to a systematic over-estimation of NEP. Finally, NBP were calculated for each crop by adding carbon inputs through organic fertilizers and carbon outputs through biomass exportation to NEP. For the three years, the Auradé NBP indicate a nearly carbon balanced ecosystem, whereas the Lamasquère NBP of about 100 $\text{ g C m}^{-2} \text{ y}^{-1}$ indicates that the ecosystem was a carbon source. Moreover, carbon inputs through organic fertilizers could induce important CH₄ and N₂O emissions, which are stronger greenhouse gases than CO₂. Therefore, a complete greenhouse gas budget at the plot scale should be investigated to fully evaluate these crop management impacts. We suggest that the differences in carbon balance between Auradé and Lamasquère are mostly due to differences in the type of farm: cereal production at Auradé and cattle breeding at Lamasquère.

Despite the fact that the carbon storage potential of croplands seems to be poor, long term monitoring experiments are very important to evaluate the carbon balance of different rotations cycles, with various climate and physical backgrounds. It will provide insights into which rotations, crop species and crop management techniques can mitigate carbon release to the atmosphere and improve carbon sequestration in the context of climate change and increasing earth population and food needs.
Acknowledgements

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Reference


