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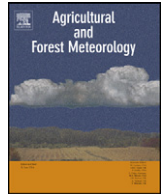
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Carbon balance of a three crop succession over two cropland sites in South West France

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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: rapeseed, 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_e) 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 $-369 \pm 33 \text{ g C m}^{-2} \text{ y}^{-1}$ 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. 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_e 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 and 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 $100 \text{ g C m}^{-2} \text{ y}^{-1}$; 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 Sivakumar (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

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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 beat (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 over 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 (day-month-year) 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-Sept-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-Sept-2005) and before sunflower sowing (plough on 29 and 30-Sept-2006 and harrow on 12-Mar-2007).

The Lamasquère plot was 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-Sept-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. Field 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 (F_{ct}), water vapour (evapotranspiration, E and latent heat, LE), sensible heat (H) and momentum (τ) have been 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 (CR5000, 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.

Table 1

Site characteristics and general information on soil and meteorology. Climatic means were measured with each site meteorological station as described in Section 2.2. Mean annual air temperatures and annual precipitations were computed with data from 18-Mar-2005 to 17-Mar-2006 (2005 values) and from October to October (2006 and 2007 values). Mean wind speed and wind rose were computed with data from 18-Mar-2005 to 01-Oct-2007. Climatic normals are “Meteo France” data from the “Toulouse Blagnac” station (visible at <http://www.infoclimat.fr/climatologie/index.php>); they correspond to means calculated over 30 years (1961–1990).

	Sites	
	Auradé	Lamasquère
Site characteristics		
Coordinates	43°54'97"N, 01°10'61"E	43°49'65"N, 01°23'79"E
Plot area [ha]	23.5	32.3
Elevation [m]	245	180
Slope [%]	2	0
Exposure	ENE	
Fetch in main wind directions [m]	260 W, 270 ESE	200 W, 140 ESE
Soil		
Class of soil texture	Clay loam	Clay
Particle analysis [% sand; % loam; % clay]	20.6; 47.1; 32.3	12.0; 33.7; 54.3
Site climates		
Mean annual temperature		
2005 [°C]	12.84	12.54
2006 [°C]	12.97	12.95
2007 [°C]	13.30	13.09
Annual precipitation		
2005 [mm]	724	681
2006 [mm]	684	620
2007 [mm]	671	615
Mean wind speed [m s ⁻¹]	2.60	1.79
Site climates		
Wind distribution		
Climatic normals		
Mean annual temperature [°C]		12.9
Annual Precipitation [mm]		655.7

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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 Lamasquère 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):

$$\text{aPPFD} = (\text{PPFD} + r_{\text{st}}\text{PPFD}) - (\text{tPPFD} + r_{\text{t}}\text{PPFD}) \quad (1)$$

where r_{st} is the soil reflectance for PPFD, $t\text{PPFD}$ is the PPFD transmitted to soil and $r_{\text{t}}\text{PPFD}$ 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. r_{st} was estimated as the slope of the linear regression between $r_{\text{t}}\text{PPFD}$ and PPFD during bare soil periods between tillage and sowing. r_{st} estimates were 0.145 ($R^2 = 0.81$) at Lamasquère and 0.231 ($R^2 = 0.82$) at Auradé. aPPFD was only calculated for periods with plant area index (PAI) higher than $1 \text{ m}^2 \text{ m}^{-2}$ to limit spatial variability errors in $t\text{PPFD}$ 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 Lamasquère 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,

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Campbell Scientific Inc, Logan, UT, USA). Soil temperature, moisture and heat flux profiles were measured with TP107 (Campbell Scientific Inc, Logan, UT, USA), CS616 (Campbell Scientific Inc, Logan, UT, USA) and HFP01 (Hukseflux, Delft, NL) probes, respectively. Three measurement repetitions were performed on each site at depths of 0.05, 0.10, 0.30 m and a single measurement was taken at depths of 0.60 and 1 m at Auradé and Lamasquère, respectively. Since 03-Nov-2006 at Auradé and 24-Aug-2006 at Lamasquère, CO₂ atmospheric concentration, air temperature and relative humidity profiles (50 and 150 cm aboveground) have been measured using GMP343 (GMP343, Vaisala, Helsinki, Finland) and HMP50 (HMP50, Vaisala, Helsinki, Finland), respectively. These measurements were then used for multi-layer CO₂ storage calculations (see Section 2.3).

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 Auradé and Lamasquère, 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, OHAUS, 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-Apr-2005 (Fig. 2(a)). For winter wheat, ten 1.5 m long rows were collected at each sampling date. Because seeds were not sown in rows, triticale 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 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:

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

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 yields were in good agreement (slope = 0.97, intercept = 19 g C m⁻², R² = 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_{ct}, E 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_{cs}) were calculated as described in Aubinet et al. (2001) but with only one measuring height for CO₂ concentration:

$$F_{cs} = \frac{P_a}{RT_a} \cdot \frac{\partial c}{\partial t} \cdot h_{ec} \quad (3)$$

where h_{ec} is the EC system height, P_a is the atmospheric pressure at h_{ec}, T_a is the air temperature at h_{ec}, R is the molar gas constant, and c is the CO₂ concentration at h_{ec}. This methodology is known to underestimate F_{cs} 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_{cs} is assumed to be low (Anthoni et al., 2004a; Moureaux et al., 2006; Suyker et al., 2005; Verma et al., 2005; Wohlfahrt et al., 2005; Xu and Baldocchi, 2004). Net ecosystem exchange (NEE) was then calculated as the sum of F_{ct} and F_{cs}. When CO₂ concentration profiles below the EC were measured, Eq. (3) was used to calculate storage in each h_i high layer of the profile. F_{cs} below the EC system was then calculated as the sum of storage in each h_i 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_{ct}, E 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_i with a 200 data point moving mean (X_{gi}) and standard deviation (X_{sdi}) as follows:

$$\text{if } X_i < X_{gi} - (2.5 \cdot X_{sdi}) \quad (4a)$$

or

$$\text{if } X_i > X_{gi} + (2.5 \cdot X_{sdi}) \quad (4b)$$

then X_i was discarded from the dataset. This procedure was performed separately for day-time and night-time data. Night-time was defined as PPFD < 5 μmol m⁻² s⁻¹ and solar elevation angles < 0°.

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 (CFP) 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 ($D_{90,i}$) 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 $D_{90,i} > D_i$, 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 $1.25 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ for NEE and 10 W m^{-2} for energy fluxes H and LE. Fluxes corresponding to an unrotated vertical wind velocity mean $w > 0.35 \text{ m s}^{-1}$ 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_E

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_E) components. The method described in Reichstein et al. (2005), based on the Lloyd and Taylor (1994) model parameters optimisation, was followed:

$$R_E = R_{\text{ref}} \cdot \exp\left(E_0 \left(\frac{1}{T_{\text{ref}} - T_0} - \frac{1}{T_a - T_0}\right)\right) \quad (5)$$

where R_{ref} is the respiration at the reference temperature T_{ref} (here 10°C therefore $R_{\text{ref}} = R_{10}$), E_0 is a parameter describing R_E sensitivity to temperature, and T_0 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 E_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_{10} was optimised with nocturnal filtered NEE for five days sliding windows with a two day step and interpolated every half-hour. Diurnal R_E was then calculated using Equation 5 with optimised E_0 and R_{10} and diurnal T_a . Diurnal GEP was finally calculated as the difference between the diurnal gapfilled NEE and the diurnal calculated R_E .

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 ($\sigma(\text{NEPu})$) 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 (NEEu) and gapfilled. All other treatments on NEEu were the same as those described in Section 2.3.2. NEP from the 100 u_* thresholds (NEPu) were then computed. $\sigma(\text{NEPu})$ was calculated as the standard deviation of all the NEPu.
- (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 ($\sigma(\text{NEPr})$) in the following steps:
 - Random errors (δ) 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:

$$\sigma(\delta) = -0.152 \text{NEE} + 0.87 \quad \text{for NEE} \geq 0 \quad (R^2 = 0.82) \quad (6a)$$

$$\sigma(\delta) = -0.204 \text{NEE} + 0.47 \quad \text{for NEE} < 0 \quad (R^2 = 0.63) \quad (6b)$$
 - 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 (NEEr). NEEr was then gapfilled, and the noisy NEP (NEPr) was computed. This last step was repeated 100 times, and $\sigma(\text{NEPr})$ was calculated as the standard deviation of all NEPr.
- (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 (NEEgap). NEEgap was then gapfilled and integrated to compute NEP (NEPgap). Gap re-introduction and NEPgap computation was done 100 times. $\sigma(\text{NEPgap})$ was calculated as the standard deviation of all the NEPgap.

Assuming a normal distribution of NEPu, NEPr and NEPgap and that these three sources of error were independent, NEP standard deviation, $\sigma(\text{NEP})$, was estimated as the quadratic sum of $\sigma(\text{NEPu})$, $\sigma(\text{NEPr})$ and $\sigma(\text{NEPgap})$. NEP uncertainty was reported at a 95%

confidence interval as $2\sigma(\text{NEP})$. 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:

$$\text{NBP} = \text{NEP} + \text{OF} + \text{Exp} \quad (7)$$

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 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 ($\text{PAI}_{\text{max}} - 0.5 \leq \text{PAI} \leq \text{PAI}_{\text{max}}$ where PAI_{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:

$$\text{NEE}_d = \frac{1}{2\theta} (\alpha - \text{aPPFD} + \beta) - \sqrt{(\alpha - \text{aPPFD} + \beta)^2 - 4\alpha\theta(\text{aPPFD} - \gamma)} \quad (8)$$

where α is the initial slope of the light response curve, β is NEE_d at light saturation, γ is the respiration term and θ is the curvature parameter ($0 < \theta \leq 1$). All fitted parameters and fitting statistics are reported in [Table 3](#). Periods with high vapour 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_{res}), computed as the difference between observed NEE and modelled NEE by Eq. (8). NEE_{res} were averaged for 1 hPa VPD bins. VPD threshold was defined as the lower VPD bin with NEE_{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_{res} were also analysed against aPPFD, soil water content (SWC) and T_a (data not shown). For aPPFD and SWC, NEE_{res} were randomly distributed around 0 with no clear pattern. These results indicate a satisfying NEE_d 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_d 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 Lamasquère 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 Lamasquère site than normals. For the 3 cropping seasons, temperature, precipitation and wind speed were slightly lower at Lamasquère 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 so 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 Lamasquère ([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 Lamasquère ([Fig. 1c](#) and [d](#)). Absolute values of SWC were higher at Lamasquère than at Auradé because of (1) a higher water retention capacity of the soil at Lamasquère due to higher clay content ([Table 1](#)) and (2) the proximity of the “Touch” river at Lamasquère. 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 Lamasquère 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 Loncée site in Belgium. Maximum growth was observed from late April to late May. PAI_{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 $1.5 \text{ m}^2 \text{ m}^{-2}$ and GEP values lower than $-8 \text{ g C m}^{-2} \text{ d}^{-1}$ even though LAI values were close to $0 \text{ m}^2 \text{ m}^{-2}$, as explained above ([Figs. 2](#) and [4](#)). AGB ranged from $324 \pm 157 \text{ g C m}^{-2}$ for Auradé sunflower in 2007 to $810 \pm 311 \text{ g C m}^{-2}$ for Lamasquère maize in 2006 ([Table 2](#)). On average, AGB were 36% lower at Auradé than at Lamasquère, but Exp were 65% lower at Auradé than at Lamasquère. This more important difference in Exp is linked to crop residues, which were 1.9 times higher at Auradé than at Lamasquère. This is

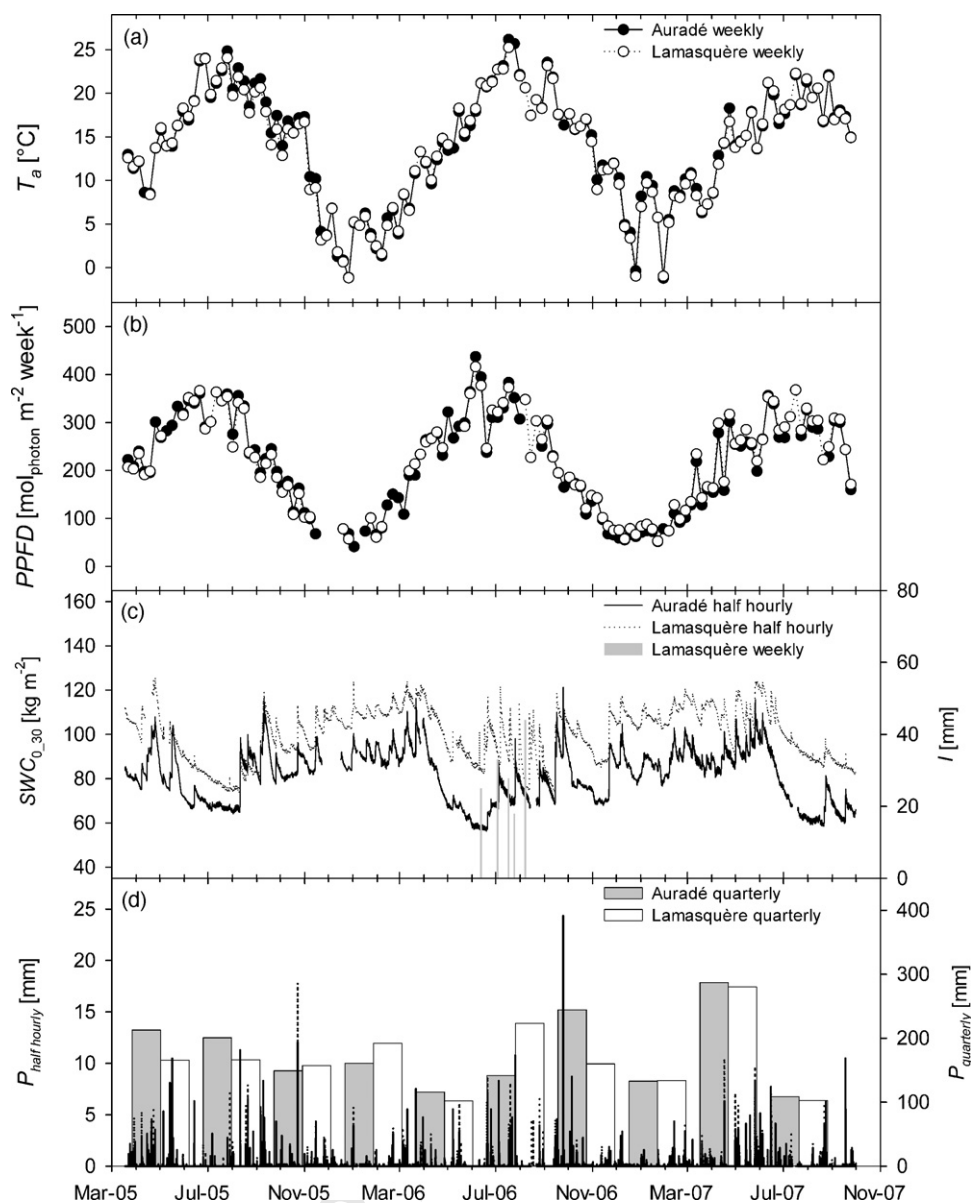


Fig. 1. Evolution of meteorological variables from 18-Mar-2005 to 01-Oct-2007. (a) Weekly averages of air temperature (T_a), and (b) weekly sums of photosynthetic photon flux density (PPFD) at Auradé (solid line and full circles) and Lamasquère (dotted line and open circles). (c and d) The half-hourly soil water content integrated between 0 and 0.3 m depth (SWC_{0-30}) and precipitation (P), respectively, for Auradé (full line) and Lamasquère (dotted line). Weekly sums of irrigation (I) for Lamasquère (vertical grey bar) and the quarterly sums of precipitation for Auradé (grey bar) and Lamasquère (white bar) are also reported on graphs (c) and (d), respectively.

577 because Lamasquère is a cattle breeding farm exporting most of
578 the aboveground biomass for cattle bedding and feeding,
579 whereas Auradé is a cereal production farm exporting only the
580 seeds. Residues were particularly low for maize in 2006 at
581 Lamasquère because all aboveground biomass was used for
582 silaging.
583

3.3. Seasonal changes in carbon fluxes

584 Net carbon fluxes over crop ecosystems are influenced by
585 different processes; some are natural (photosynthesis and
586 respiration), and others are caused by human activities (organic
587 fertilization, tillage, ...). Fig. 4 presents the evolution of gross
588 ecosystem production (GEP, i.e., ecosystem carbon uptake by
589 both crop and weed photosynthesis) and ecosystem respiration
590 (R_E , i.e., autotrophic and heterotrophic respiration). In order to
591 separate the impacts of temperature from the other possible R_E
592 driving variables (phenology, growth, water, management, etc.)
593

593 the normalized ecosystem respiration at a reference temperature
594 of 10 °C (R_{10}) is also reported in Fig. 4.
595

3.3.1. Gross ecosystem production (GEP)

596 The dynamics of GEP of the different crops were close to
597 those of PAI (Figs. 2 and 4). For winter crops, GEP remained low
598 like PAI until March, except for winter wheat in 2007 at
599 Lamasquère. Indeed, winter wheat development occurred earlier
600 in winter 2006–2007 because of the warm episodes described
601 above. Therefore, absolute GEP values were high from December
602 to March compared with winter wheat at Auradé in 2006.
603 Overall, during crop development, absolute values of GEP
604 increased to a maximum value (GEP_{max}) corresponding to
605 PAI_{max} . Daily carbon fluxes at maximum crop development are
606 reported in Table 2 for each crop. For winter crops, GEP_{max}
607 ranged between $-15.4 \text{ g C m}^{-2} \text{ d}^{-1}$ for rapeseed reached on 24-
608 May-2005 at Auradé and $-18.9 \text{ g C m}^{-2} \text{ d}^{-1}$ for winter wheat
609 reached on 21-Apr-2007 at Lamasquère. These estimates agree
610

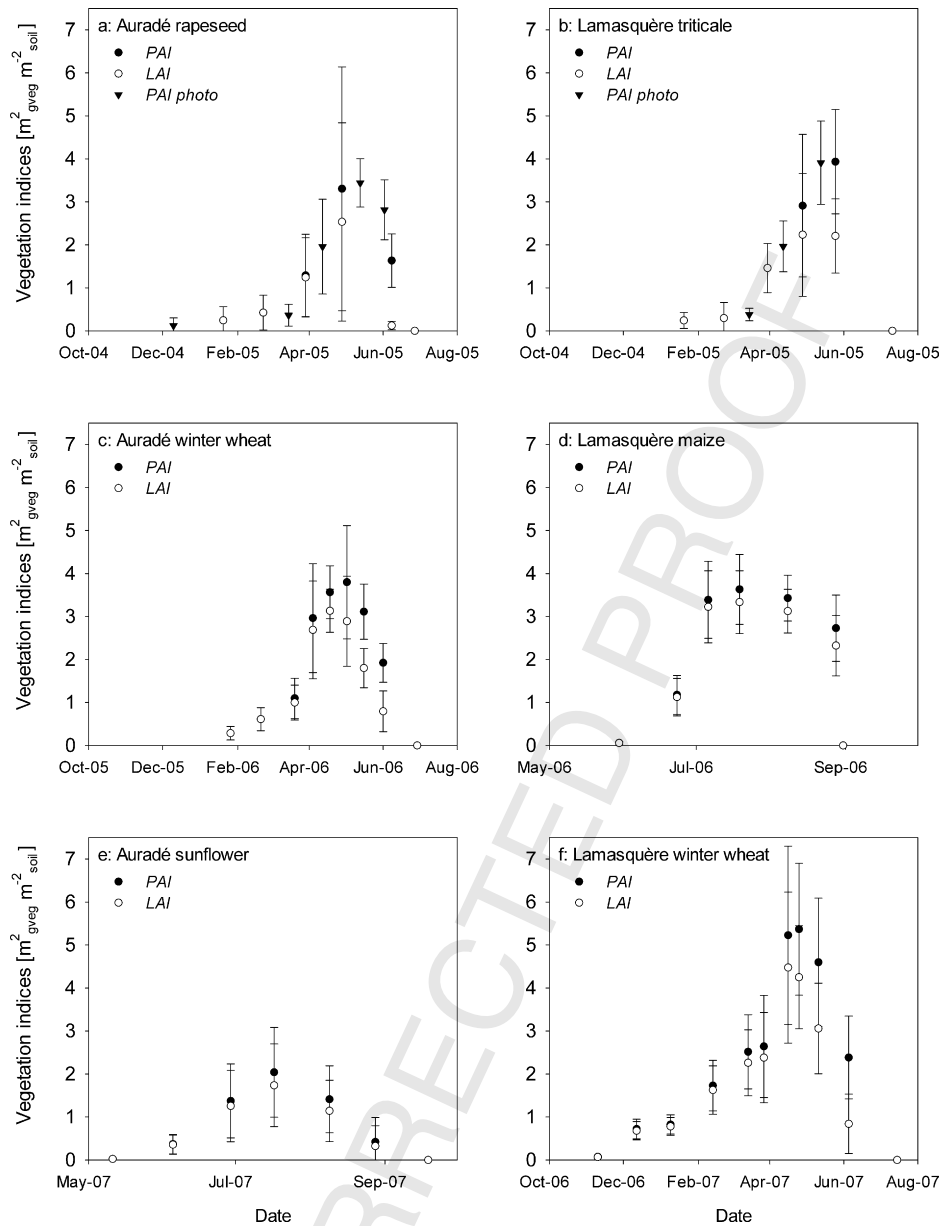


Fig. 2. Evolution of vegetation indices: plant area index (PAI) and leaf area index (LAI) for 2005 (a and b), 2006 (c and d) and 2007 (e and f) crops. The units are green vegetation area per soil area. Vertical full lines (error bars) are \pm standard deviation of each measurement mean. For (a) and (b), full triangles represent PAI measured by means of hemispherical photography (see Section 2.2.3).

610
611 with those reported over other winter wheat crops,
612 $-17.4 \text{ g C m}^{-2} \text{ d}^{-1}$ and $-16.4 \text{ g C m}^{-2} \text{ d}^{-1}$ for the Ponca (USA)
613 and Soroé (Denmark) sites, respectively (Falge et al., 2002),
614 about $-16 \text{ g C m}^{-2} \text{ d}^{-1}$ at the Gebesee (Germany) site (Anthoni
615 et al., 2004a) and $-15 \text{ g C m}^{-2} \text{ d}^{-1}$ at the Loncée (Belgium) site
616 (Aubinet et al., submitted for publication). For maize, GEP_{max}
617 was $-19.6 \text{ g C m}^{-2} \text{ d}^{-1}$. Suyker et al. (2005) reported higher
618 absolute GEP values of about $-27 \text{ g C m}^{-2} \text{ d}^{-1}$. However, GEP_{max}
619 per leaf area unit were higher at our site than in Suyker et al.
620 (2005), with respective values of $5.8 \text{ g C m}^{-2} \text{ leaves d}^{-1}$ (max-
621 imum $\text{LAI} = 3.4 \text{ m}^2 \text{ m}^{-2}$) and $4.5 \text{ g C m}^{-2} \text{ leaves d}^{-1}$ (maximum
622 $\text{LAI} = 6 \text{ m}^2 \text{ m}^{-2}$). The low GEP_{max} observed at our site was
623 probably not caused by physiological stress but by low LAI
624 values. Moreover, the high GEP_{max} per leaf area unit observed at
625 our site could be interpreted as higher light use by the
626 photosynthetic tissues caused by lower shadow effects at lower
627 LAI. The difference in LAI can be explained by differences in
628 irrigation. At our site, the irrigation amount was two times

628
629 lower than in Suyker et al. (2005) (precipitation + irrigation
630 during vegetation period were respectively 413 and 749 mm).
631 Verma et al. (2005) reported maximum LAI values of $3.9 \text{ m}^2 \text{ m}^{-2}$
632 over rainfed maize with precipitation of 433 mm during the
633 vegetation period, which is comparable to our study. Differences
634 in maize variety (grain production in Suyker et al. (2005) and
635 silaging at our site) and associated management practices might
636 also explain LAI differences. Sunflower had the lowest absolute
637 GEP_{max} rate of $-13.7 \text{ g C m}^{-2} \text{ d}^{-1}$, probably because of the lower
638 PAI of this crop ($\text{PAI}_{\text{max}} = 2 \text{ m}^2 \text{ m}^{-2}$) compared to the others.
639 Then crops entered into senescence, and the absolute values of
640 GEP decreased until harvest. For maize, the interruption in
641 carbon assimilation was sudden due to an early harvest just
642 after the beginning of senescence. This event occurred so that
643 the maize was used for silaging.

644 After harvest (see Section 2.1 and Fig. 5 for dates), absolute
645 values of GEP often increased again due to the re-growth of
646 seeds that fell during harvest and the growth of weeds under

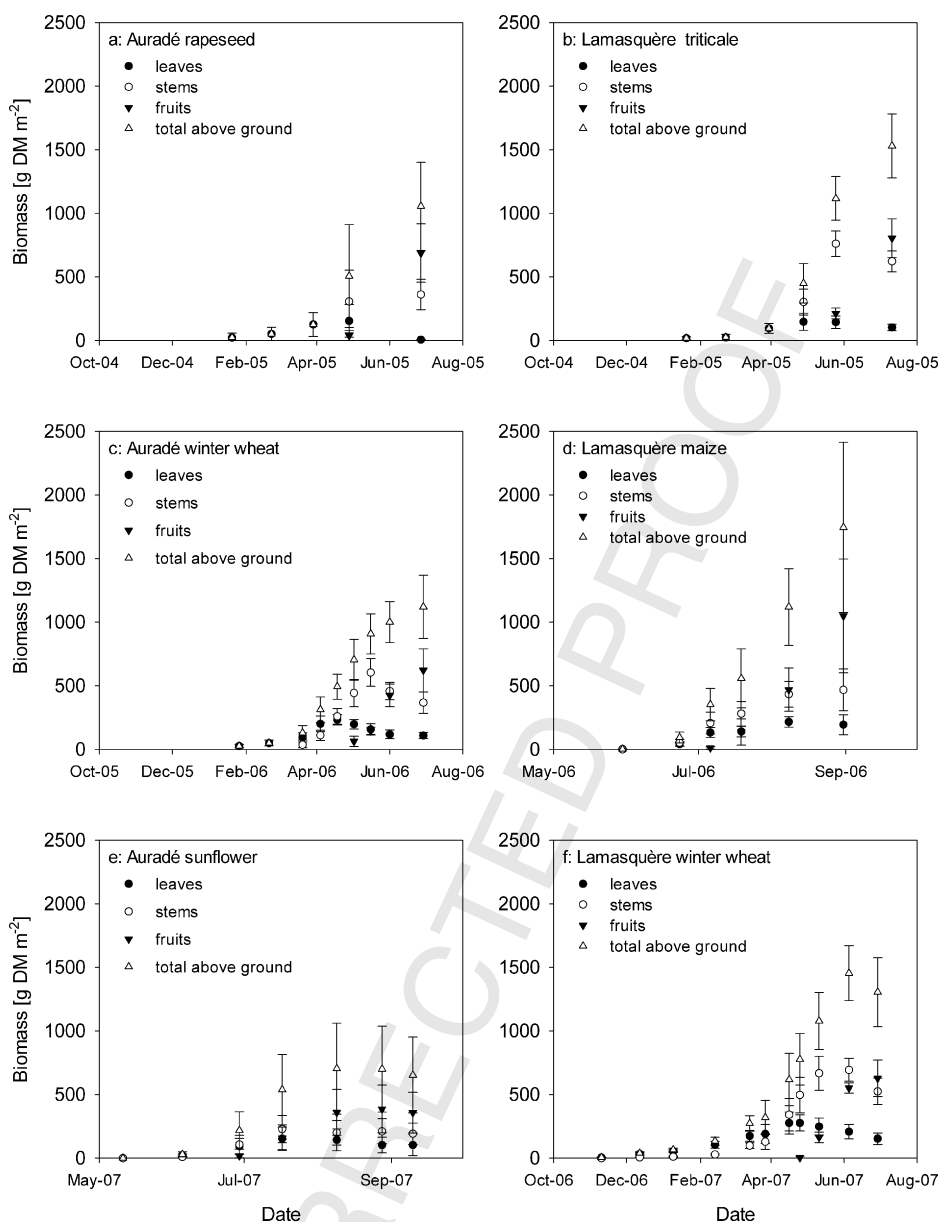


Fig. 3. Evolution of biomass in the different plant organs for 2005 (a and b), 2006 (c and d) and 2007 (e and f) crops. Vertical full lines (error bars) are \pm the standard deviation of each measurement mean. Fruits correspond to siliqua plus flower biomass for rapeseed, ear biomass for winter wheat and triticale, ear plus flower biomass for maize and seed plus flower biomass for sunflower.

646 favourable meteorological conditions. A long re-growth
647 period was observed at Lamasquère after the triticale harvest
648 in 2005, with PAI values of about $0.7 \text{ m}^2 \text{ m}^{-2}$ (estimate
649 with hemispherical photography) and GEP values reaching
650

5.65 $\text{g C m}^{-2} \text{ d}^{-1}$ on 22-Oct-2005. Two other re-growth events
651 occurred at Auradé at the end of summer and in fall 2005 with
652 absolute GEP values smaller than for the Lamasquère re-growth.
653 Re-growth was more important after 2005 crops than after 2006
654

Table 2

Values at the maximum of crop development of plant area index (PAI_{max}), daily ecosystem respiration ($R_{\text{E,max}}$) and gross ecosystem production (GEP_{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.

Sites	PAI_{max} ($\text{m}^2 \text{ m}^{-2}$)	$R_{\text{E,max}}$ [$\text{g C m}^{-2} \text{ d}^{-1}$]	GEP_{max} [$\text{g C m}^{-2} \text{ d}^{-1}$]	AGB [g C m^{-2}]	Residues [g C m^{-2}]	Exp [g C m^{-2}]
Auradé						
Rapeseed 2005	3.4 ± 0.6	8.0	-15.4	482 ± 158	269 ± 76	213 ± 61
Winter wheat 2006	3.8 ± 1.3	7.0	-15.6	516 ± 115	237 ± 66	279 ± 42
Sunflower 2007	2.0 ± 1	7.3	-13.7	324 ± 157	220 ± 67	104 ± 36
Lamasquère						
Triticale 2005	3.9 ± 1.2	7.0	-17.1	663 ± 109	158 ± 41	505 ± 39
Maize 2006	3.6 ± 0.8	11.0	-19.6	810 ± 311	4 ± 3	806 ± 57
Winter wheat 2007	5.4 ± 1.5	11.5	-18.9	600 ± 125	213 ± 82	386 ± 47

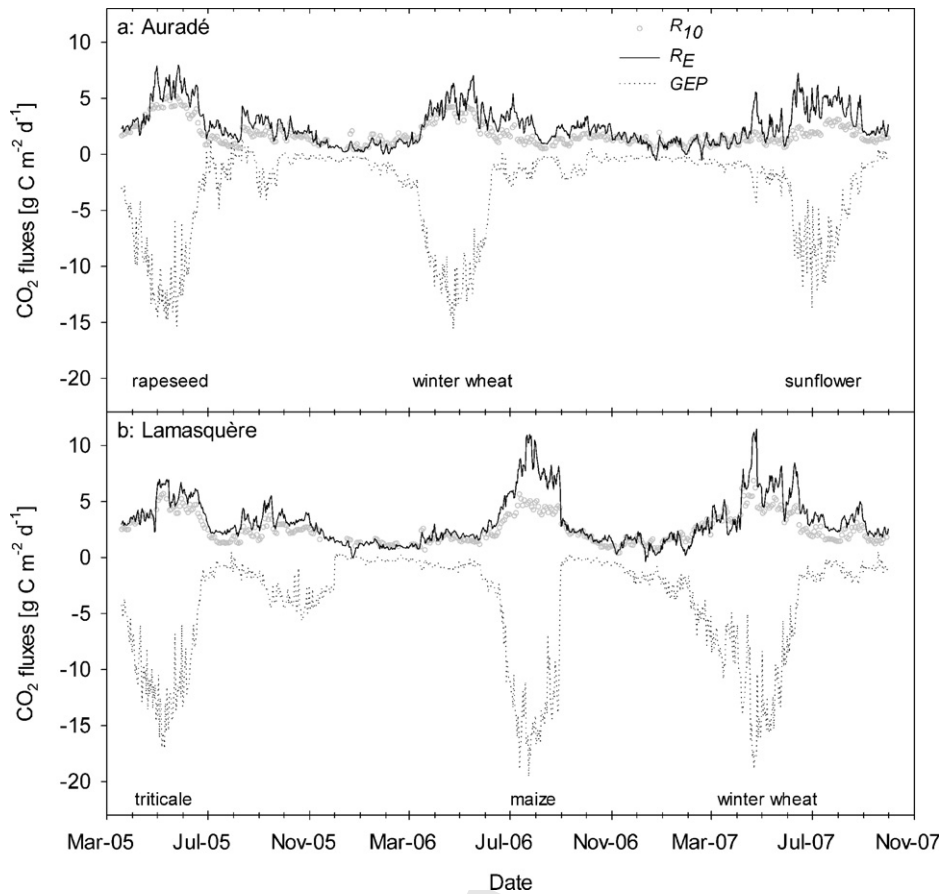


Fig. 4. Evolution of carbon fluxes for (a) Auradé and (b) Lamasquère plots from 18-Mar-2005 to 01-Oct-2007. The solid line is the daily ecosystem respiration (R_E), the dotted line the daily gross ecosystem production (GEP) and the full grey circles the ecosystem respiration at a reference temperature of 10°C (R_{10}). Gaps in R_{10} correspond to large gaps in filtered NEE or in T_a inducing failure in the fitting operation (see Section 2.3.3). The different crops species are reported for each site under the curves. Atmospheric convention was used for this representation; fluxes from ecosystem to atmosphere are positives, and inversely, fluxes from atmosphere to ecosystem are negatives.

654
655 and 2007 crops because of important rainfall events and high
656 temperatures in Fall 2005 (Fig. 1). After maize and sunflower
657 crops, the stubbles were ploughed into the soil, and winter
658 wheat was seeded; therefore, no re-growth was observed. For
659 the other crops, re-growth was stopped by the different tillage
660 operations (see Section 2.1 for dates). Low absolute GEP values
661 during winter were caused by (1) low temperatures that
662 reduced ecosystem activity for winter crops and (2) absence
663 of vegetation during the winter and spring preceding the
664 summer crop.

665 3.3.2. Ecosystem respiration (R_E)

666 R_E and R_{10} seasonal dynamics were quite similar. This suggests
667 that, at a seasonal scale, crop development is a more important
668 driving variable for R_E than temperature. This hypothesis is
669 confirmed by measurements at our sites showing that autotrophic
670 respiration represents the largest proportion of R_E during
671 vegetation periods (Sagnier and Le Dantec, personal communica-
672 tion). R_{10} and R_E evolution differed more for summer crops
673 probably because of high summer temperature affecting R_E .

674 R_E globally followed the same dynamics as GEP and PAI during
675 crop development. However, in spring 2005, R_E was delayed
676 compared to GEP. A sudden R_E increase occurred in late April,
677 whereas absolute GEP had already increased. Lags between GEP
678 and R_E dynamics have already been observed by Falge et al. (2002)
679 in temperate deciduous and boreal coniferous forests. Both
680 phenological and climatic factors could explain this lag. Heading
681 and flower emergence are known to induce an increase in crop
682 respiration (Balocchi, 1994), and the late R_E increase occurred at

683 this phenological stage. However, as R_E delay was not visible for
684 2006 and 2007 winter crops, this reinforces the fact that phenology
685 was not the only factor. Low temperatures until late April followed
686 by a rapid temperature increase and 45 mm of rainfall between 20-
687 Apr-2005 and 01-May-2005 (Fig. 1) could have induced a sudden
688 R_E increase. These two meteorological events can contribute to soil
689 micro-organism activation and quickening of crop development.
690 Maximum R_E values ($R_{E,max}$) for winter crops ranged between
691 7.0 g C m⁻² d⁻¹ on 17-May-2006 for winter wheat at Auradé and
692 11.5 g C m⁻² d⁻¹ on 24-Apr-2007 for winter wheat at Lamasquère.
693 These observed values are higher than those reported in Falge et al.
694 (2002) over two winter wheat plots (3.1 g C m⁻² d⁻¹ and
695 5.6 g C m⁻² d⁻¹), but agree with values of 8 g C m⁻² d⁻¹ reported
696 by Aubinet et al. (submitted for publication) over a winter wheat
697 crop. As GEP_{max}, $R_{E,max}$ estimated over maize in the present study
698 was lower than the one (13 g C m⁻² d⁻¹) reported by Suyker et al.
699 (2005), because of the LAI difference explained above.

700 During intercropping periods, R_E was relatively low at both
701 sites, but peaks occurred. As these peaks affected both R_E and
702 R_{10} , they were not controlled by temperature. Generally rainfall
703 events, ploughing, residue incorporation into the soil and re-
704 growth could explain these peaks. For example, R_E and R_{10}
705 increased in the beginning of August 2005 at Auradé, which
706 occurred following incorporation of residues and plant re-
707 growth into the soil by the cover crop on 04-Aug-2005 and a
708 55 mm rainfall event between 10-Aug-2005 and 11-Aug-2005.
709 In the absence of vegetation on the plot at this time, this R_E
710 increase could be explained by micro-organism activation
711 caused by higher water and substrate availability for decom-

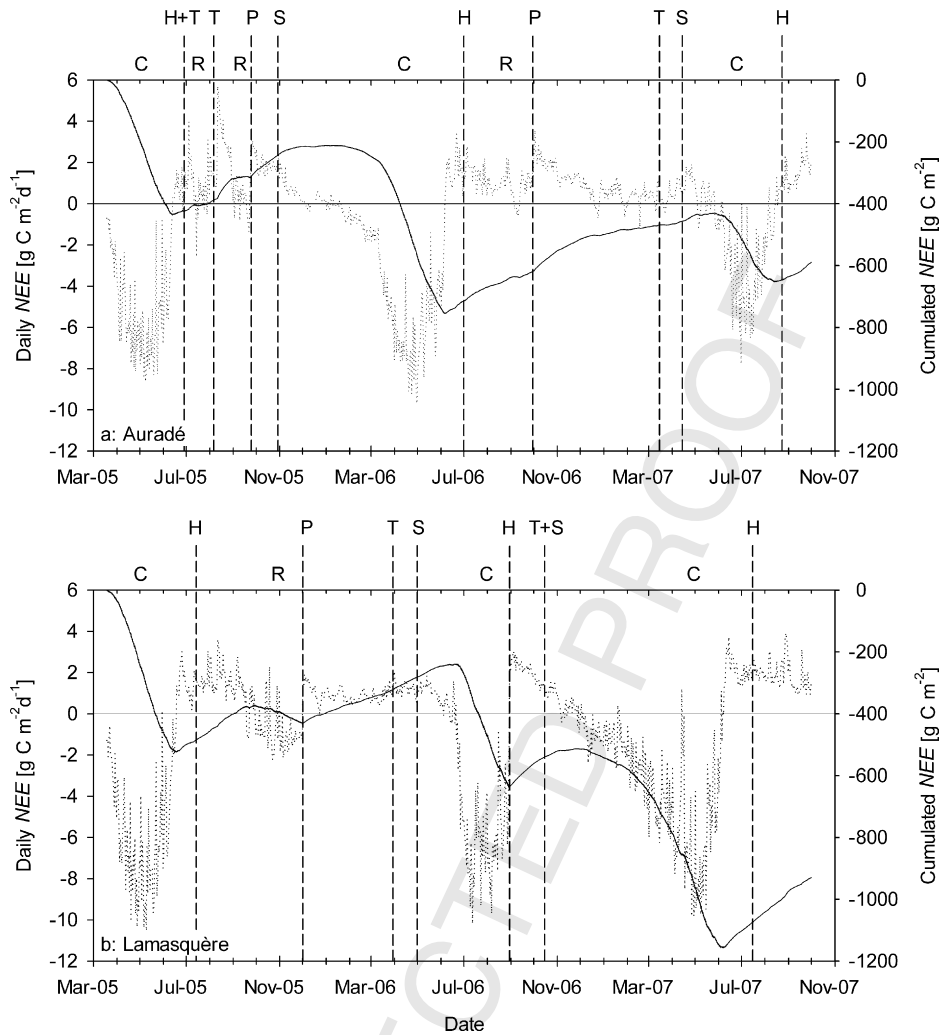


Fig. 5. Daily net ecosystem exchange (NEE) evolution (left axis) and cumulated values of NEE (right axis) from 18-Mar-2005 to 01-Oct-2007 at the Auradé (a) and Lamasquière (b) plots. Crop development (denoted as C) and re-growth (denoted as R) periods were reported at the top of each subplot. Annotations 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.

711 position. Generally, high R_E rates in summer after harvest in
712 2005 for both sites and in 2006 at Auradé were mainly caused by
713 re-growth and soil water availability (Figs. 1 and 4).
714

715 3.3.3. Net ecosystem exchange (NEE) and carbon storage dynamics

716 NEE dynamics allow the determination of GEP and R_E
717 importance in the ecosystem carbon dynamics, whereas cumu-
718 lated NEE allows the identification of carbon storage or release
719 periods (Fig. 5). A negative slope on the cumulated NEE curve
720 means that the ecosystem behaves as a carbon sink ($GEP > R_E$),
721 and a positive slope means that the ecosystem behaves as a
722 carbon source ($GEP < R_E$). Overall, the dynamics were well-
723 marked with alternating carbon sequestration and carbon
724 release periods corresponding to crop growth and bare soil,
725 respectively. For the three observed seasons, Lamasquière was
726 a stronger carbon sink than Auradé without considering manage-
727 ment effects (see Section 3.5.2).

728 Development of crops (denoted C) appeared quite different for
729 winter and summer crops. For winter wheat, NEE values were close
730 to $0 \text{ g C m}^{-2} \text{ d}^{-1}$ ($GEP = R_E$) from the beginning of November until
731 February at Auradé in 2006 and only until December at
732 Lamasquière in 2007. Then, for all winter crops, NEE values became
733 negative, and the ecosystem stored carbon until the beginning of
734 June. Maximum absolute NEE values of -8.6 , -9.7 , -10.5 and
735 $-9.8 \text{ g C m}^{-2} \text{ d}^{-1}$ were observed at Auradé for rapeseed and winter

wheat and at Lamasquière for triticale and winter wheat,
736 respectively. Between May and June, GEP decreased because
737 senescence began, although R_E remained high; therefore, carbon
738 storage became less important with decreasing absolute NEE
739 values. In June, senescence was observed with a fast change in the
740 sign of NEE, which became positive because R_E values became
741 higher than absolute GEP values. For summer crops (maize and
742 sunflower), NEE values were positive until June, about one and a
743 half months after sowing. The NEE became negative and maximum
744 absolute NEE values of -7.8 and $-10.2 \text{ g C m}^{-2} \text{ d}^{-1}$ were observed
745 at Auradé for sunflower and at Lamasquière for maize, respectively.
746 The ecosystem stored carbon from June to August for sunflower
747 and from mid-June to harvest (denoted H) for maize. The reversal
748 from a carbon sink to a carbon source was more progressive for
749 sunflower than for winter crops because of a slower senescence.
750 For maize, the inversion was sudden because it was harvested,
751 whereas it was still green just after the beginning of senescence.
752

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

760 from a source to a sink. Negative NEE values down to
761 $-2 \text{ g C m}^{-2} \text{ d}^{-1}$ were observed during re-growth events in 2005,
762 and it allowed a net carbon storage of -57 g C m^{-2} .

763 Tillage (denoted T for superficial tillage and P for deep
764 ploughing) affected the cumulated NEE in two ways, as described
765 in Sections 3.3.1 and 3.3.2: (1) it stopped carbon assimilation from
766 re-growth events, and (2) it could contribute to important soil
767 respiration increases when associated with rainfall events and
768 incorporation of plant residues as on 10-Aug-2005 at Auradé.
769 Tillages before summer crops at Auradé and Lamasquère and the
770 non-inverting tillage between maize and winter wheat at
771 Lamasquère had no visible impact on NEE.
772

3.4. NEE response to light

773 Ecosystem net carbon fluxes of the different crops were
774 compared in terms of response to light in order to evaluate the
775 influence of climatic variables, species and sites on NEE as well as
776 annual carbon balance.
777

3.4.1. Climatic control on NEE response to light

778 The VPD threshold above which NEE modelled by Eq. (8) were
779 overestimated (see Section 2.3.5) was on average 27% lower for
780 winter crops than for summer crops (Table 3). This shows that
781 summer crops are more adapted to air high VPD than winter crops;
782 their higher stomatal conductance was underlined by their higher
783 net carbon fixation rate at high VPD.
784

785 Except for rapeseed at Auradé in 2005, the datasets were split into
786 two parts according to light quality. The first one corresponded to
787 the ratio of diffuse PPFD to total PPFD (d/t) lower than 0.5 (clear sky
788 conditions) and the other to d/t higher than 0.5 (cloudy conditions).
789 It can be seen that for aPPFD above $400 \mu\text{mol m}^{-2} \text{ s}^{-1}$, NEE_d values
790 were higher for diffuse conditions (Fig. 6). Such observations have

790 already been reported for many ecosystems (Alton et al., 2007; Gu
791 et al., 2002; Law et al., 2002; Moureaux et al., 2006; Suyker et al.,
792 2004). Considering all crops except rapeseed, the mean β and α were
793 higher ($-51 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ and $-0.051 \text{ mol mol}^{-1}$, respec-
794 tively) in diffuse light conditions than in direct light conditions
795 ($-33 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ and $-0.028 \text{ mol mol}^{-1}$). Large differences
796 in parameterisation between diffuse and direct conditions were also
797 observed by Gu et al. (2002) on different ecosystems (Scots pine
798 forest, aspen forest, tallgrass prairie, mixed forest and wheat crops).
799 Higher values of β and α for diffuse light conditions were probably
800 caused mainly by the limitation of shadow effects with a more
801 homogeneous distribution of radiation among all leaves in plant
802 canopies (Gu et al., 2002). It induced better light use efficiency for
803 NEE and limited saturation effects.
804

805 The determination coefficient (R^2) and the root mean square
806 error (RMSE) were respectively 35% higher and 37% lower for
807 cloudy conditions than for clear sky conditions. It was probably
808 because aPPFD were usually higher for clear sky conditions, and
809 this corresponds to the saturation part of the global light response
810 curve. Therefore, aPPFD was probably not the most important
811 driving variable influencing NEE_d during clear sky conditions
812 (Baldocchi, 1994); indeed, air and soil temperature and humidity,
813 wind speed and measurement error are more important driving
814 variables of NEE_d in clear sky conditions.

3.4.2. Species and site impact on NEE response to light

815 Comparison of crop behaviours and fitting parameters in both
816 clear sky and cloudy conditions (Fig. 6 and Table 3) shows that light
817 saturation seems to be correlated to PAI_{max} values (Table 2).
818 Indeed, low β , as observed for sunflower at Auradé in 2007,
819 correspond to low PAI_{max} while high β , as observed for winter
820 wheat at Lamasquère in 2007, correspond to high PAI_{max} . With
821 similar aPPFD values in both cases, the lower the PAI is, the more
822

Table 3

Best fit parameters of Equation 8 (α is the initial slope of the light response curves, β is NEE_d at light saturation, γ is the respiration term and θ is the curvature parameter ($0 < \theta \leq 1$)) and associated statistics (R^2 is the determination coefficient, and RMSE the root mean square error) for each crop at maximum crop development ($\text{PAI}_{\text{max}} - 0.5 < \text{PAI} \leq \text{PAI}_{\text{max}}$) at the Auradé and Lamasquère plots. Eq. (8) was fitted for clear sky conditions data ($d/t < 0.5$), cloudy conditions data ($d/t \geq 0.5$) and for all data (clear sky and cloudy conditions). Values in brackets correspond to VPD thresholds expressed in hPa. NEE and aPPFD data were selected below this threshold (see text).

Data	Parameters				Statistics			
	α [$\mu\text{mol CO}_2 \mu\text{mol}_{\text{photon}}$]	β [$\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$]	γ [$\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$]	θ	R^2	RMSE [$\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$]	n	
All data								
Auradé								
Rapeseed 2005 (11)	-0.0670	-38.43	4.39	0.63	0.88	3.54	568	
Winter wheat 2006 (9)	-0.0410	-33.52	2.42	0.90	0.86	3.71	504	
Sunflower 2007 (14)	-0.0357	-19.12	3.26	0.94	0.82	3.00	473	
Lamasquère								
Triticale 2005 (15)	-0.0548	-52.77	4.46	0.00	0.79	4.66	307	
Maize 2006 (17)	-0.0501	-42.57	5.50	0.82	0.80	5.26	614	
Winter wheat 2007 (10)	-0.0885	-67.65	9.34	0.00	0.85	5.19	315	
Diffuse/total <0.5								
Auradé								
Winter wheat 2006	-0.0250	-29.89	0.72	0.99	0.81	3.22	200	
Sunflower 2007	-0.0420	-19.70	4.37	0.90	0.38	3.68	139	
Lamasquère								
Triticale 2005	-0.0239	-45.71	0.10	0.80	0.52	5.11	150	
Maize 2006	-0.0249	-31.60	0.83	1.00	0.61	5.49	277	
Winter wheat 2007	-0.0229	-36.97	-1.20	1.00	0.59	5.68	103	
Diffuse/total >0.5								
Auradé								
Winter wheat 2006	-0.0444	-37.86	2.71	0.90	0.92	3.03	304	
Sunflower 2007	-0.0398	-28.01	3.42	0.70	0.87	2.54	334	
Lamasquère								
Triticale 2005	-0.0510	-55.76	4.39	0.31	0.86	3.71	157	
Maize 2006	-0.0486	-51.55	5.34	0.87	0.90	3.93	337	
Winter wheat 2007	-0.0792	-87.02	8.85	0.00	0.92	3.78	212	

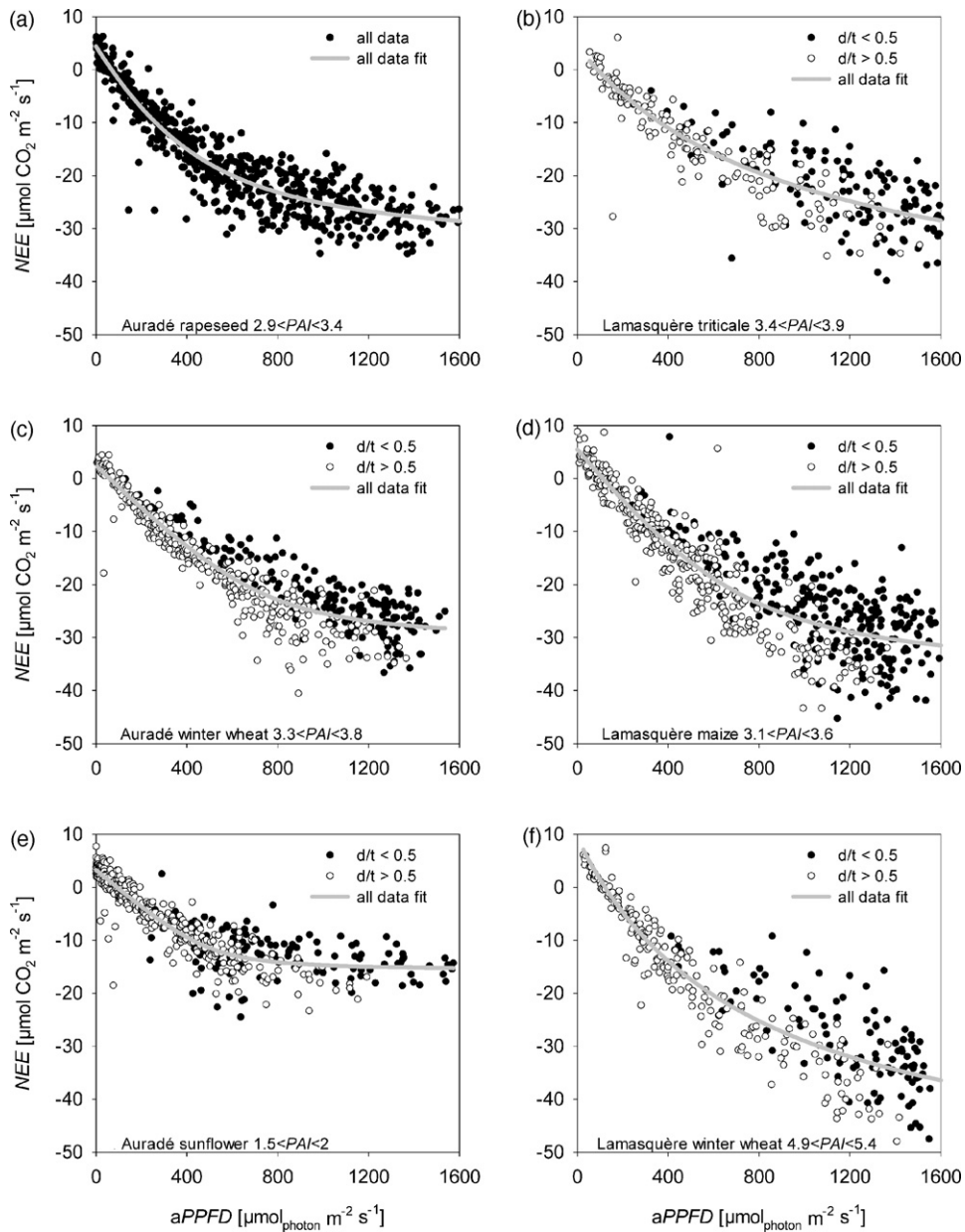


Fig. 6. Light response curves at maximum crop development ($\text{PAI}_{\text{max}} - 0.5 < \text{PAI} \leq \text{PAI}_{\text{max}}$) below the VPD threshold (see text) for 2005 (a and b), 2006 (c and d) and 2007 (e and f) crops. Net ecosystem exchange (NEE) is shown as a function of photosynthetic photon flux density absorbed by vegetation (aPPFD). In (a), all data are represented with full circles. In (b–f), full circles are data corresponding to a ratio of diffuse to total PPFD < 0.5 (clear sky conditions) and open circles to a ratio of diffuse to total PPFD ≥ 0.5 (cloudy conditions). On each plot, Eq. (8) fitted over all the data (clear sky and cloudy conditions) is also represented with a grey solid line. Fitted parameters and statistics are reported in Table 3.

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 α , which was 60% lower for sunflower than for Lamasquère 2007 winter wheat. For all other crops, PAI_{max} were similar ($3.4 \text{ m}^2 \text{ m}^{-2} < \text{PAI}_{\text{max}} < 3.9 \text{ m}^2 \text{ m}^{-2}$). It is noteworthy that no marked differences in α and β were observed between C3 winter crops (rapeseed, winter wheat and triticale) and the C4 summer crop (maize). Indeed, Baldocchi (1994) observed lower α values for maize than for winter wheat crop, but it was caused by lower PPFD 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) R_E 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_d 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 $-286 \pm 23 \text{ g C m}^{-2} \text{ y}^{-1}$ for rapeseed in 2005 at Auradé to $-369 \pm 33 \text{ g C m}^{-2} \text{ y}^{-1}$ for winter

Table 4
Annual net ecosystem production (NEP) at different crop sites and for different crop species.

Crop species	NEP, (g C m ⁻² y ⁻¹)	Site/Year	Reference
Summer crops			
Maize (mean value)	-576	Bondville 1997, 1999, 2001	Hollinger et al. (2005)
Rainfed maize (mean value)	-454	Mead 2001, 2002	Verma et al. (2005)
Irrigated maize (mean value)	-480	Mead 2001–2003	Verma et al. (2005)
Maize (conventional and reduce tillage)	-290 to -300	Rosemount 2003	Baker and Griffis (2005)
Maize	-186 ± 42	Lamasquère 2006	This study
Potato	-49 to 29	Gebesee 2002	Anthoni et al. (2004b)
Soybean (conventional and reduce tillage)	-50 to -85	Rosemount 2002	Baker and Griffis (2005)
Soybean (mean value)	-33	Bondville 1998, 2000, 2002	Hollinger et al. (2005)
Soybean (mean value)	18 to 48	Mead 2002	Verma et al. (2005)
Spring barley	210	Jokioinen 2001	Lohila et al. (2004)
Sugar beet	-610	Lonzée 2004	Moureaux et al. (2006)
Sunflower	28 ± 18	Auradé 2007	This study
Winter crops			
Rapeseed	-286 ± 23	Auradé 2005	This study
Triticale	-335 ± 42	Lamasquère 2005	This study
Winter wheat	-183	Ponca 1997	Falge et al. (2001)
Winter wheat	-185 to -245	Gebesee 2001	Anthoni et al. (2004a)
Winter wheat	-324 ± 20	Auradé 2006	This study
Winter wheat	-369 ± 33	Lamasquère 2007	This study
One year rotation			
Winter wheat + maize	-197.6	Yucheng 2003	Jun et al. (2006)
Winter wheat + maize	-317.9	Yucheng 2004	Jun et al. (2006)

852
853 wheat in 2007 at Lamasquère (Table 4). Despite its large annual GEP,
854 maize NEP was only -186 ± 42 g C m⁻² y⁻¹. The ratio of annual GEP
855 to annual R_E , denoted ψ , allows the determination of the respective
856 contribution of crop carbon assimilation by photosynthesis and
857 ecosystem respiration to NEP (Falge et al., 2002). The mean value of ψ
858 for winter crops was 1.34. For maize, ψ was 13% lower than for winter
859 crops ($\psi = 1.17$). However, annual GEP were similar in both cases
860 (-1310 g C m⁻² y⁻¹ on average for winter crops and
861 -1286 g C m⁻² y⁻¹ for maize). The difference in ψ was therefore
862 explained by the large observed difference in annual R_E
863 (982 g C m⁻² y⁻¹ on average for winter crops and 1100 g C m⁻² y⁻¹
864 for maize). Sunflower was a carbon source on an annual basis with a
865 NEP of 28 ± 18 g C m⁻² y⁻¹ ($\psi = 0.97$). This low value compared to
866 maize is the result of a low annual GEP of -803 g C m⁻² y⁻¹ and R_E of
867 831 g C m⁻² y⁻¹. We suggest that NEP differences observed among
868 winter crops and among summer crops were mostly due to
869 differences in crop carbon assimilation efficiency (see Section 3.4)
870 and to year to year climatic variations. However, these factors could
871 not fully explain NEP differences between winter and summer crops.
872 At our sites, summer crop NEP values were in absolute 76% lower than
873 winter crops. It is therefore important to consider the season length of
874 carbon assimilation. For 2006 and 2007 crops, the season length of
875 carbon assimilation was calculated as the number of days between
876 sowing and harvest with negative daily NEE. It was not calculated for
877 2005 crops, because flux measurements started after the beginning of
878 the season of carbon assimilation. The season length was 53% shorter
879 for summer crops (76 and 86 days for maize and sunflower,
880 respectively) than for winter crops (156 and 189 days for winter
881 wheat in 2006 at Auradé and 2007 at Lamasquère, respectively). The
882 season length was particularly long for 2007 winter wheat at
883 Lamasquère because of the warm 2007 winter. This emphasizes the
884 fact that long bare soil periods can counteract the ecosystem carbon
885 storage on an annual basis by carbon losses through heterotrophic
886 respiration. Compared to NEP values found at other instrumented
887 crop sites (Table 4), NEP values obtained at our site were on the same
888 order of magnitude but with some noticeable differences. Absolute
889 NEP values were 44% and 35% lower for winter wheat at the Ponca and
890 Gebesee sites, respectively, (Anthoni et al., 2004a; Falge et al., 2001)
891 than for the mean NEP of our winter crops. It may be explained by
892 differences in climate, which is more continental and with lower

893 temperatures at these two sites compared to our oceanic climate and
894 therefore conducive to lower ecosystem productivity. The low LAI and
895 early harvest of maize resulted in a 59% lower NEP in our study
896 compared with values found in the literature (Baker and Griffis, 2005;
897 Hollinger et al., 2005; Verma et al., 2005). Sunflower NEP was
898 comparable with low carbon assimilation rates encountered for
899 soybean (Baker and Griffis, 2005; Hollinger et al., 2005; Verma et al.,
900 2005) and potato (Anthoni et al., 2004b) with NEP close to neutral.
901 The stronger sink of carbon was observed at the Lonzée sugar beet
902 crop in Belgium (Moureaux et al., 2006) and the stronger source at the
903 Jokioinen spring barley crop in Finland (Lohila et al., 2004). For the
904 Chinese site of Yucheng (Jun et al., 2006), carbon storage seemed a bit
905 low compared to all the other sites because two crops (winter wheat
906 and maize) were cultivated in one year; therefore, bare soil periods
907 were limited. However, this comparison between sites is relatively
908 uncertain because of differences in dates concerning the beginning
909 and the end of the period use for annual NEP calculation, which were
910 sometimes not explicitly reported. It is therefore important to
911 harmonize and specify it for future NEP inter-comparisons exercises.

912 NEP uncertainty ($2\sigma(\text{NEP})$) estimated in the present study
913 ranged between ± 18 g C m⁻² y⁻¹ for sunflower at Auradé and
914 ± 42 g C m⁻² y⁻¹ for triticale and maize at Lamasquère. This estima-
915 tion of NEP uncertainty is in the same range of values as those
916 reported in the Baldocchi (2003) review over different sites. In that
917 study, NEP uncertainty ranged from ± 30 g C m⁻² y⁻¹ at Harvard
918 forest to ± 68 g C m⁻² y⁻¹ for a short bog with different estimations
919 methods. Dragoni et al. (2007) calculated an uncertainty in NEP
920 caused by measurements' random error with a Monte Carlo
921 simulation approach that varied between ± 10 and
922 ± 12 g C m⁻² y⁻¹. These results were very close to our uncertainty
923 in NEP caused by measurements' random error that varied between
924 ± 4 and ± 7 g C m⁻² y⁻¹ at our sites. Richardson and Hollinger (in
925 press) used a similar approach than in the present study to estimate
926 NEP uncertainty due to measurements random error and to long gaps
927 in the data set. These authors found results very close to our global
928 uncertainty estimate, ranging between ± 25 and ± 44 g C m⁻² y⁻¹ at
929 different forest sites. Independent of the method used, NEP
930 uncertainty estimates seem relatively stable across different sites.

931 Table 5 reports the impacts of methodology on NEP calculation.
932 Differences in NEP were very limited and were always in the

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_{*c} threshold detection and gapfilling (B), with a calculation of the storage term (F_{cs}) from one point of the CO₂ concentration measurement (C) and with the simultaneous application of A, B and C. Units are g C m⁻² y⁻¹.

Site/Year	This study	A: fixed 90-day periods	B: conventional stationarity	C: F_{cs} from 1 point	A + B + C
Auradé					
2005	-286 ± 22	-295 ± 22	-277 ± 21	-286 ± 22	-287 ± 22
2006	-324 ± 20	-319 ± 19	-313 ± 19	-324 ± 20	-307 ± 19
2007	28 ± 18	24 ± 18	36 ± 19	31 ± 20	33 ± 19
Lamasquère					
2005	-335 ± 42	-352 ± 29	-331 ± 41	-335 ± 42	-342 ± 28
2006	-186 ± 42	-204 ± 34	-182 ± 36	-194 ± 37	-192 ± 30
2007	-369 ± 33	-389 ± 27	-362 ± 36	-375 ± 33	-381 ± 27

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_{*c} 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 CO₂ concentration is only noticeable for 2007 NEP at Auradé and

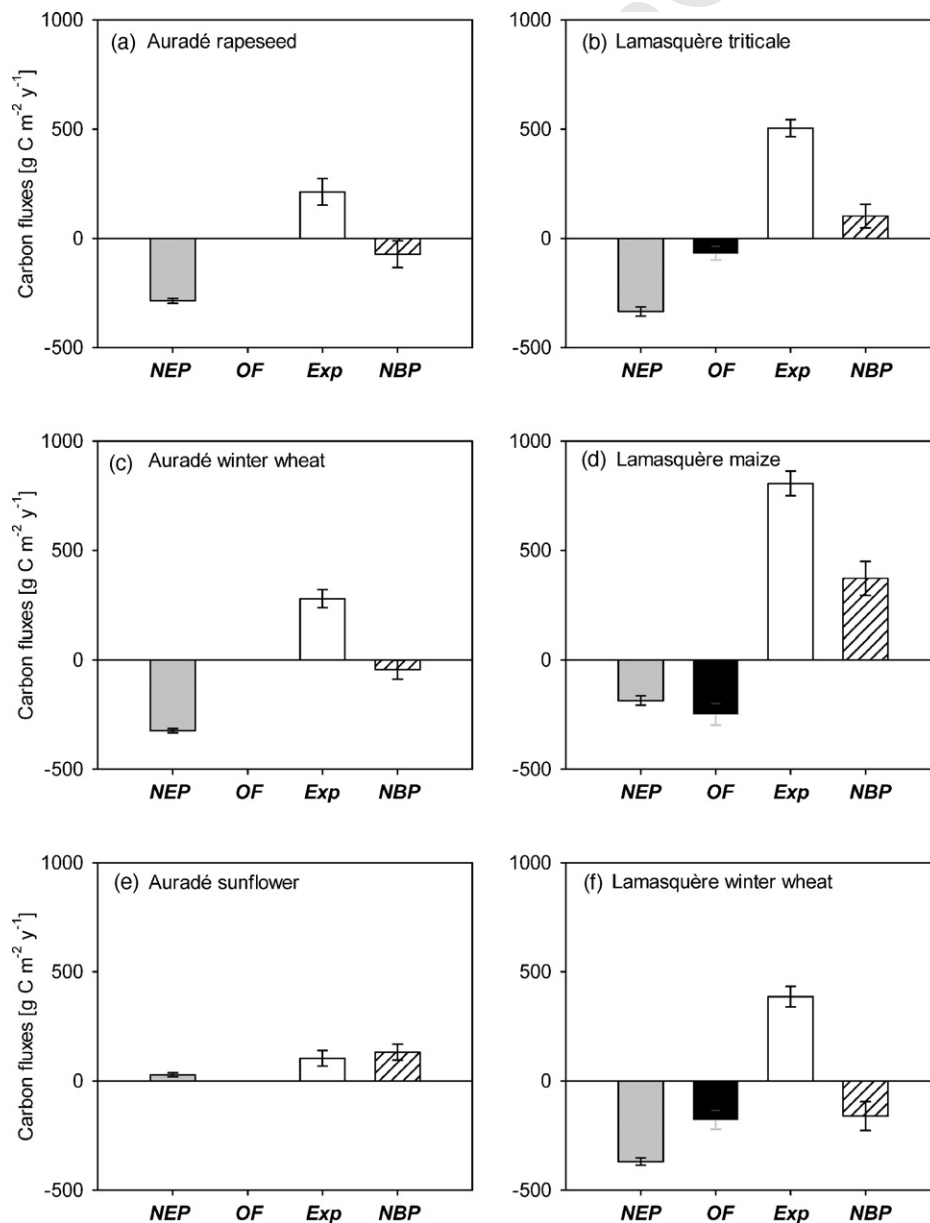


Fig. 7. The annual carbon balance at the plot scale. (a), (c) and (e) are rapeseed, winter wheat and sunflower at Auradé, and (b), (d) and (f) are triticale, maize and winter wheat at Lamasquère. Grey bars represent net ecosystem production (NEP), black bars are organic fertilization (OF), white bars 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.

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_{cs} is important, calculation of F_{cs} from one point should result in an underestimation of NEP. Mean diurnal variation of half-hourly F_{cs} data was 2.6 times higher at Lamasquère than at Auradé (not shown). At Auradé F_{cs} 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_{cs} calculation from one point all together resulted in no systematic 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 ± 31 to $-249 \pm 49 \text{ g C m}^{-2} \text{ y}^{-1}$. As a consequence, carbon inputs (NEP + OF) were on average 58% lower at Auradé than at Lamasquère, whereas NEP were only 35% lower. However, Lamasquère carbon exportations were 2.8 times higher than Auradé Exp (Table 2). As a consequence, for 2005 and 2006 crops, NBP were negative at Auradé and positive at Lamasquère. For sunflower in 2007 at Auradé, positive NEP resulted in a source of carbon of $132 \pm 37 \text{ g C m}^{-2} \text{ y}^{-1}$ considering Exp. The significant carbon sink for the winter wheat in 2007 at Lamasquère may be explained in two ways: (1) absolute NEP was the highest observed of the six crops, and (2) Exp was less important compared to 2005 and 2006 at Lamasquère (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 NBP close to neutrality: some studies found non-significant low carbon sinks (Baker and Griffis, 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. Anthoni 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 beat/winter wheat/potato/winter wheat, Aubinet et al. (submitted for publication) observed a slighter 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_E 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_E , 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 (PAI, 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 within 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.

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