Deliverable D6.10

Methods for biomass and yield products based on crop modelling

V 1.0

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D6.10 – Methods for biomass and yield products based on crop modelling version 3

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Abstract (for dissemination)

In this report, the modeling approach (SAFYE-CO2 model) for simulating the biomass, yield, evapotranspiration, CO2 fluxes and annual carbon & water budgets of cropland, based on remote sensing products (Land cover maps and LAI maps) will be described and detailed. The added value and novelties of Sensagri will also be presented. Last the strategy for validating the model’s output will be described as well as some results of validation for winter wheat sunflower ans maize.

Keywords

modeling, remote sensing, crops

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1 R = Document, report; DEM = Demonstrator, pilot, prototype; DEC = Websites, patent fillings, videos, etc; OTHER; ETHICS = Ethics requirement

2 PU = Public; CO = Confidential (Consortium and Commission Services); EU-RES = Restreint UE; EU-CON Confidentiel UE; EU-SEC = Secret UE (Commission Decision 2005/444/EC)
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1. Introduction

Scope of the document

In the emerging Copernicus Earth monitoring era, Europe provides Earth Observation (EO) data from Sentinel-1 (S1) and Sentinel-2 (S2) on a free and open data policy basis. In response of the EO Work programme ‘EO-3-2016: Evaluation of Copernicus Services’, Sentinels Synergy for Agriculture (SENSAGRI) aims to exploit the unprecedented capacity of S1 and S2 to develop an innovative portfolio of prototypes agricultural monitoring services. When used alone either optical or radar sensors allow the mapping of crop types. However more robust, accurate, frequently updated and comprehensive crop maps are expected from the seldom exploited synergy of both types of measurements. The same holds when dealing with crop LAI estimates and crop modeling. Previous studies have demonstrated that fusion of optical and radar data opens up prospects for enhanced crop modeling capabilities (Revill et al., 2013). In this document, we therefore present a modeling approach that could benefit from high spatial and temporal resolutions (HSTR) remote sensing LAI products derived from S1 and 2, combined with a simple crop model named SAFYE-CO2 (Veloso, 2014; see D6.08) and a strategy to collect in-situ data for models’ calibration and validation. This combined approach, summarized in Figure 1, opens new perspectives for advanced agro-ecosystems modeling and monitoring at regional or global scales. This document will present the model (principle, equations and calibration procedure) and also some results of validation.

![Figure 1. SAFYE-CO2 model diagram illustrating the main inputs of the model and the assimilation of series of remotely sensed LAI maps for calibrating the model parameters for estimating biomass and yield, evapotranspiration, CO₂ fluxes, as well as C&water budgets.](image-url)
As green LAI dynamic maps based on Sentinel 1 & 2 were validated late in the project over our area of study, we continued to use remote sensing data from the Formosat-2 and SPOT satellites to produce the LAI maps (based on the inversion of a the BV-NET tool ; Baret et al., 2007) that will be used to calibrate the model over the French site. Crop maps will be used to fix crop specific parameters as input in the model.

The dynamic LAI maps are used for calibrating the phonological parameter of the SAFYE-CO2 crop models. This semi-empirical model, based on Monteith’s light-use efficiency theory and adapted for remote sensing coupling, is calibrated and evaluated in terms of LAI, biomass, yield estimates, photosynthesis (GPP for Gross Primary Production), autotrophic respiration (R_a), heterotrophic respiration (R_h), net CO₂ flux (NEE), carbon budget (NECB for Net Ecosystem Carbon Budget), evaporation (E), transpiration (Tr), soil water content (SWC) and water budget. The initial SAFY-CO2 model (see D6.03) was coupled with a soil water budget module, based on the FAO-56 method (presented in D6.08). In this document, the equation used to calculate evaporation was modified since, in the FAO-56 method, the evaporative demand is calculated in reference to a 12 cm grassland instead of a bare soil. This modification of the FAO-56 improved significantly our water budgets estimates.

**Added value and novelties of SENSAGRI**

The main added values and novelties in SENSAGRI are listed here below:

- The model has been parametrised and validated for several crops found in South West France (winter wheat, maize, sunflower). In the D6.03 and D6.08 the model was only parametrised for winter wheat.

- The parameter of the equation allowing to calculate the light use efficiency and accounting for the effect of diffuse radiation over crop photosynthesis (GPP) has been recalibrated over 5 crop flux sites in Europe for more genericity (i.e. the Auradé, Lamasquère and Grignon sites in France as well as the Oensingen and Lonzée sites in Switzerland ans Belgium, respectively). In the D6.08 this equation was calibrated at our sites only (i.e. Auradé and Lamasquère).

- The model has been coupled with a soil water module that allows us to simulate the components of the crop water cycle and to account for water stress on biomass and yield production (presented in D6.08). The modeled SWC has been used as an input variable to improve simulation of heterotrophic respiration. In this version of the document, the FAO-56 method has been modified in order to better simulate bare soil evaporation as in Soarès et al. (1988). The modified FAO56 method improves our evaporation estimates and reduce the bias on the annual water budgets.

- In the coming month, the model will be evaluated and applied over a larger area thanks to the data that have been collected in WP7, to the LAI and crop maps that have been produced over 3 Sentinel 2 tilesin France. Up to now, the model was evaluated only against data collected at the Regional Spatial Observatory, over an area that was 25*25 km.

- In the future, thanks to the combined use of S1 and S2 to produce dynamic LAI maps, the modeling approach will become more operational. Indeed, up to now the modeling approach depends on LAI maps produced with optical EO only. Therefore, long periods of clouds, as in spring 2008 in our area, do not allow to produce dynamic LAI maps over the course of the crop development and therefore the model can be inoperable.
Table 1. List of the SAFYE-CO2 crop model parameters, notation, units, values or range and the methods of calibration for the winter wheat crop.

<table>
<thead>
<tr>
<th>Description</th>
<th>Notation</th>
<th>Units</th>
<th>Value/Range</th>
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**Notations, abbreviations and acronyms**

Some notations, abbreviations and acronyms are listed here below but the parameters and variables (and associated units) used by the model are listed in Table 1.

- CESBIO: Centre d’Etudes Spatiales de la BIOsphère
- DAM: Dry Aboveground Biomass
- ELUE: Effective Ligth Use Efficiency
- EO: Earth Observation
- FAPAR: Fraction Absorbed of Photosynthetically Active Radiation
- GIS: Geographical Information Software
- GPP: Gross Primary Production
- HI: Harvest Index
- HSTR: High Spatial and Temporal Resolutions
- LAI: Leaf Area Index
- NEE: Net Ecosystem Exchange
- NEP: Net Ecosystem Production
- NECB: Net Ecosystem Carbon Budget
- NPP: Net Primary Production
- OSR: Regional Space Observatory
- PAR: Photosynthetic Active Radiation
- Ra: Aurotrophic Respiration
- Reco: Respiration of the Ecosystem
- Rdf: Global diffuse incoming radiation
2. Model description

The SAFYE-CO2 model is essentially composed of two modules: the plant module, similar to the SAFY-CO2 model that allows to simulate the components of the cropland carbon budget, was developed from the original SAFY (Simple Algorithm For Yield estimates, Claverie et al., 2012; Duchemin et al., 2008) but it also allows evaluating the crop water requirements (i.e., the amount of water needed by the soil-vegetation system for evapotranspiration). SAFY is a daily time step crop model that simulates the LAI time series, Dry Aboveground Biomass (DAM) and grain yield. SAFY is driven by daily incoming global radiation (Rg) and the cumulated daily mean air temperature (Ta). This approach is based on Monteith and Moss’s (1977) light-use efficiency theory, which links the production of the total DAM with the photosynthetically active portion of solar radiation (PAR) absorbed by the plants. In SAFY, the ratio of photosynthesis (GPP) / autotrophic respiration (Ra) is assumed constant when estimating the DAM from the absorbed Photosynthetic Active Radiation (PAR which is estimated directly from the Rg). In SAFYE-CO2, as in the SAFY-CO2 model, the GPP is first estimated as a function of the absorbed PAR. Next, the other components of the net CO₂ fluxes and carbon budget are calculated (such as heterotrophic and autotrophic respiration, DAM, yield, etc.). Therefore, because the GPP and Ra are both simulated, the GPP/Ra ratio is not constant. Consequently, variable climatic and environmental conditions can be properly accounted for through crop development. This difference between SAFY and SAFYE-CO2 implies that the effective light-use efficiency (ELUE, see Eq. (4)) has different meanings in both models.

The second module of SAFYE-CO2 is a soil module, which describes the water transfers in the soil-vegetation-atmosphere continuum. The coupling of both modules is achieved by means of three main variables (at daily step): the LAI, the water stress (Ks) and the superficial soil moisture (He). The soil module is based on the SAFYE model (Duchemin et al., 2005), which is a modified version of the FAO-56 method. In comparison to the existing SAFYE model, the SAFYE-CO2 model is also capable of simulating the CO₂ fluxes, in addition to the standard outcomes: crop production, evapotranspiration and soil water content. The soil module allows an assessment of the water availability and it characterizes the crop water stress (Duchemin et al., 2005). In our modeling approach, the evapotranspiration is estimated base on the dual-crop coefficient approach of the FAO56 method.
separating the evaporation and transpiration contributions. In the soil module calculations, only the vertical flows are considered, neglecting the runoff horizontal flows. The soil is represented by two horizontal ‘infinite’ layers: the surface (top) and the deep layers. During the vegetative period, the soil deep layer is divided in two, for generating a root layer just between the superficial and the deeper layer. Therefore, three soil layers are involved in soil water transfer mechanisms: (1) a superficial layer that works as an interface with the atmosphere, and supplies water to the deeper soil layers; (2) an intermediate layer that extends with the root zone; and (3) a deep layer that produces base flow. The water budget is calculated at daily step, over a period of time chosen by the user. The soil module module is composed of three main steps: a) assessment of the evolution of the roots development and update of the soil water content and of the available water in the root and deep soils reservoirs; b) computation of the gravity fluxes between the surface, root and deep layers; c) computation of the diffusive fluxes.

The following sub-sections present the SAFY-CO2 formalisms. In the following equations, the variables that are calculated for the current day are associated with the index “i”, and the variables estimated for the previous day are associated with the index “i-1”. All of the parameters and variables (and associated units) used by the model are listed in Table 1. This model was originally coded in Matlab but to fulfill the objectives of the SENSAGRI project and for being able to run the model on large EO domains, the model has been re-coded in Python, the code has be optimised and coupled with the Geographical Information Software (GIS) platform at CESBIO. The model that has been validated for winter wheat (SAFY has been also validated for summer crops) will also be validated for summer crops (e.g. sunflower) over the French. In the coming month, the model will be applied over the study sites in Spain and Italy, which are representative of the European crop diversity. In order to refine the specifications of the products (model outputs) and to iteratively assess the services, actors of the agricultural sector have been involved using a Living Lab approach. The combination of user-centred approach and of state-of-the-art algorithms will establish a sound foundation for deciding of a new Copernicus land service.

2.1. The plant module

2.1.1. GPP estimates

In the SAFYE-CO2 model, the GPP [Eq.(1)] is a function of the incoming global radiation (Rg), the fraction of radiation absorbed by the photosynthetically active elements of plants (fAPAR) [Eq.(2)], the climatic efficiency (εc) (which is the ratio of incoming photosynthetically active radiation to global radiation), the effective efficiency of the conversion of absorbed radiation to fixed CO2 through plant photosynthesis (ELUE) [Eq.(4)] a temperature stress function (FT) and a the water stress function (Ks) [Eq.(29)]. The water stress Ks calculated by the water module (see section 2.2.1) limits the GPP when water stress conditions are met. In SAFY-CO2, the photosynthesis estimation could already be impacted by temperature stresses (by means of the F(Ta) function); but all the others stresses (water, nitrogen, ...) were “included”, in some way, in the light-use efficiency term (fELUE). The introduction of the water stress function allows better accounting of the effects of water stress episodes over the crop production; the Ks is therefore decoupled from the fELUE.
To account for the fraction of green plant tissues remaining during the senescent phase, a multiplicative coefficient (sR10, Béziat et al., 2009) was added to this formalism to estimate the GPP [Eq. (1)]. The sR10 coefficient is set to 1 from the day of emergence (D0) until the day when senescence begins. From this day until the end of the simulation, sR10 is the quotient between the LAI value of the current day and the maximum seasonal LAI value multiplied by a corrective factor, Cs [Eq.(3)]. At first, the senescence phase acts on the lower portions of the plant (closer to the soil) and on the higher canopy elements. Thus, the actual phenological senescence may be more accentuated than that detected by the satellite observations, which would require a corrective factor. Therefore, the Cs coefficient was included in the computation of sR10 to correct for the effects of senescence over the simulated fluxes.

The effects of the diffuse global radiation fraction over canopy photosynthesis are not usually considered in crop models when estimating crop productivity. However, measurements, including some realised at our sites, have indicated that the efficiency of canopy gas exchange is very sensitive to the diffuse components of incoming solar radiation (Béziat et al., 2009; Hollinger et al. 1998; Roderick et al., 2001). Indeed, when the fraction of diffuse global radiation increases, the proportion of shaded leaves within the canopy decreases. Furthermore, because the photosynthetic rate of leaves is usually saturated at high incoming radiation, the leaves with low irradiance will be more efficient, and reductions in the volume of shade leaves within the canopy indicate that the canopy will be more efficient in the presence of low and diffuse irradiance (Roderick et al., 2001). Thus, it is expected that the photosynthetic efficiency should increase as the fraction of diffuse global radiation increases. Models that ignore the diffuse components of solar radiation are likely to incorrectly simulate GPP dynamics (de Pury & Farquhar, 1997; Roderick et al., 2001). Consequently, our approach is to replace the constant ELUE parameter by considering a function based on the daily fraction of diffuse and global incoming radiation (Rdf/Rg).
Because diffuse incoming global radiation (Rdf) is not often measured on the field and global incoming radiation (Rg) data are widely available (e.g. SAFRAN data in France or ERA-5 data over Europe), we used the De Jong (1980) approach to estimate the Rdf/Rg ratio over our study area from available Rg. Once the fraction of diffuse radiation was calculated (Rdf/Rg), we established a relationship linking it with the radiation use efficiency (RUE). The RUE was defined as the ratio of GPP to Rg. Based upon field data at 5 European crop flux sites, we established an exponential function between the Rdf/Rg ratio and the RUE with one fitted parameter \( b \) (see (Eq. 4)). In addition to the effects of Rdf/Rg, the photosynthesis process could also be affected by other climatic variables, such as temperature and the water vapor pressure deficit (VPD). For example, low VPD values could correspond with low temperatures that reduce plant respiration and with high diffuse-to-total radiation ratios, which enhance carbon fixation at the canopy scale (Alton et al., 2007; Béziat et al., 2009; Moureaux et al., 2006). Because temperature is already considered when estimating the GPP (see Eq.(2)), we analyzed the relationships between the daily VPD and RUE and between the VPD and diffuse ratio Rdf/Rg. This analysis allowed us to make the methodological decision of considering the effects of the diffuse fraction on GPP estimates but not the effects of the VPD. Indeed, we observed that the VPD values were linearly (and negatively) correlated with the Rdf/Rg (\( R^2=0.55 \)) and that no significant correlation (\( R^2=0.00029 \)) was found between the VPD and the GPP residuals (the difference between the observed GPP and the estimated GPP values).

### 2.1.2. NPP and Ra estimates

The NPP (for Net Primary Production), representing the amount of biomasse produced, is defined as the GPP minus the autotrophic respiration (Ra) [Eq.(5)]. To estimate Ra, we used an approach that separates the Ra into two components, maintenance respiration (\( R_m \)) and growth respiration (\( R_g \)) (McCree, 1974) [Eq.(6)]. \( R_m \) was calculated from the NPP of the previous day and a maintenance coefficient, \( m\_m \) [Eq.(7)]. The coefficient \( m_R \) corresponds to the fraction of maintenance respiration per NPP unit. Because \( m\_R \) responds strongly to temperature (Amthor, 2000), it was estimated by using a “\( Q_{10} \) type” equation [Eq.(8)]. In this equation, \( R_{10} \) is the reference respiration at 10°C.

The \( R_g \) was calculated using the method described by Amthor (1989) and improved by Choudhury (2000), as shown in Eq. (9). The constant \( Y_G \) is the growth conversion efficiency.

\[
NPP_i = GPP_i - R_u, \tag{5}
\]

\[
R_u = R_m + R_g, \tag{6}
\]

\[
R_m = \frac{NPP_{i-1}}{10} \times m\_R \times R10_i \tag{7}
\]

\[
m\_R = R_{10} \times Q_{10}^{\frac{\left(T_m - 10\right)}{10}} \tag{8}
\]

\[
R_g = (1 - Y_G) \times (GPP_i - R_m) \tag{9}
\]
Finally, the total NPP was divided into root (NPP<sub>r</sub>) and aerial (NPP<sub>a</sub>) components. To estimate NPP, we used a root-to-shoot ratio (RtS) that was calculated according to the methods proposed by Baret et al. (1992) [Eqs. (10), (11)]. The NPP<sub>a</sub> was deduced from the NPP and NPP<sub>r</sub> [Eq.(12)] and was used to estimate aboveground biomass production.

\[ NPP_i = NPP_i \times RtS_i \]  \hspace{1cm} (10)

\[ RtS_i = fr = fr_\infty + (fr_0 - fr_\infty)e^{-c \left( \frac{SMT_i - SMT_{t0}}{SMT_{t0} - SMT_{t1}} \right)} \]  \hspace{1cm} (11)

where SMT is the sum of temperature; D<sub>0</sub> is the emergence date; and D<sub>s</sub> is the first day of senescence.

The root fraction (fr) is expressed as the number of growth degree days (°Cd) since emergence; fr<sub>0</sub> is the extrapolated fr value at emergence; fr<sub>∞</sub> is the asymptotic value of fr; and c is the relative rate of decrease.

\[ NPP_{a_i} = NPP_i - NPP_{r_i} \]  \hspace{1cm} (12)

### 2.1.3. LAI, DAM and Yield estimates

The DAM was estimated by dividing the NPP<sub>a</sub> by the coefficient C<sub>veg</sub>, which represents the plant carbon content [Eq.(13)]. Next, the daily aboveground biomass production was converted into the LAI according to the SAFY equations (see Duchemin et al., 2008).

The grain yield estimation [Eq.(14)] depends on the total biomass production (at the end of the vegetative period) and on a constant harvest index (HI).

In some cases, the straw can be exported at harvest. From the perspective of regional scale applications, this term (strawexp) was estimated as a function of the total straw biomass (strawtotal), which corresponds with the final aboveground biomass (DAM<sub>max</sub>) minus the final grain yield, and the sc parameter [Eq.(20)], which was estimated from in situ data.

\[ DAM_i = \frac{NPP_{a_i}}{C_{veg}} \]  \hspace{1cm} (13)

\[ Yield = DAM_{max} \times HI \]  \hspace{1cm} (14)
2.1.4. NEE, Rh, Reco and NECB estimates

The NEE was calculated as the difference between the NPP and the carbon losses due to heterotrophic respiration ($R_h$) [Eq.(15)].

$$\text{NEE}_i = \text{NPP}_i - R_h$$

In SAFY-CO2, $R_h$ was calculated using an empirical function depending only on the soil temperature. In SAFYE-CO2, $R_h$ was calculated using an empirical equation [Eq.(43)] that depends on soil water content and soil temperature ($T_s$) (see section 2.2.2).

The ecosystem respiration ($R_{eco}$) is defined as the sum of $R_a$ and $R_h$ [Eq. (16)]. Table 1 summarizes the new parameters of the SAFY-CO2 model in addition to those that were already present in the original SAFY model.

$$R_{eco} = R_a + R_h$$

To compute the annual carbon budget (NECB), carbon import ($C_{inp}$) and export ($C_{exp}$) terms were added to the annual cumulated net CO$_2$ exchange (NEE) between the plot and the atmosphere (NEP, for Net Ecosystem Production) [Eq.(17)]. The carbon input term ($C_{inp}$) corresponds to the amount of carbon brought to the plot by the seeds at sowing and by the organic fertilizers. The amounts of organic fertilizer (OF) spread at our experimental sites were given by the farmer and converted to carbon equivalents after performing a carbon content analysis. The carbon export term ($C_{exp}$) corresponds to the amount of carbon exported from the plot at harvest. It corresponds either to the final grain yield [Eq.(18)] or it must be computed from the grain yield and the exported straw [Eqs.(19) and (20)]. The NEP is usually computed from October 1st to September 30th because this period usually corresponds with an agricultural year.

$$\text{NECB} = \text{NEP} + C_{inp} + C_{exp}$$

$$C_{exp} = \text{Yield} \quad \text{if only grain is exported};$$

$$C_{exp} = \text{Yield} + (\text{DAM}_{max} - \text{Yield}) \times sc \quad \text{if grain + straw is exported};$$

$$sc = \frac{\text{straw}_{exp}}{\text{straw}_{total}} = \frac{\text{straw}_{exp}}{\text{DAM}_{max} - \text{Yield}}$$
The difference between the net carbon inputs (here corresponding to the sum of NEP and $C_{\text{inp}}$) and the carbon loss at harvest ($C_{\text{exp}}$) reflects the short-term evolution of the soil organic carbon content. The micrometeorological convention is adopted, with a negative NEP when the ecosystem is fixing carbon and a positive NEP when the ecosystem is losing carbon. The $C_{\text{exp}}$ term is considered as an instant release of carbon to the atmosphere and is positive. The $C_{\text{inp}}$ term is a carbon input into the field and has therefore a negative sign. Finally, the annual NECB indicates if the ecosystem is a carbon sink (NECB negative) or a carbon source (NECB positive).

2.1.5. Plant module parametrization and calibration

The parameters of the SAFY-CO2 module can be divided into the following three main classes according to the method by which they are set: i) based on literature review, ii) based on in situ measurements and iii) optimized using time series of the remotely-sensed LAI. The parameters included in the two first classes are set as equal for all of the investigated fields and years of study. The parameters in the third category include the ELUE and the phenological parameters. These parameters are set using an iterative method. The ELUE is optimized and set to the same value for all years and fields. The phenological parameters are field-specific and are optimized individually for each field and each year by minimizing the error between the simulated LAI time series and those derived from the remote sensing data. In the following sections, the model parametrization and calibration procedure is presented in details for winter wheat. The model parameters for sunflower and maize are presented in the Supplementals.

2.1.5.1. Parameters from the literature review

This group includes the following parameters: the climatic efficiency ($\varepsilon_C$), the specific values of air temperature related to plant functioning ($T_{\text{min}}$, $T_{\text{max}}$ and $T_{\text{opt}}$), the polynomial degree ($\beta$) of the temperature-stress-function $F_T$, the growth respiration conversion efficiency parameter ($Y_G$), the plant maintenance respiration parameters ($Q_{10}$ and $R_{10}$), the heterotrophic respiration parameters ($R_{\text{Rh}0}$ and $Q_{10}$). Climatic efficiency ($\varepsilon_C$) is considered constant in space and time and is fixed at 0.48 (Varlet-Grancher et al., 1982). The values of air temperature related to plant functioning ($T_{\text{min}}$, $T_{\text{max}}$ and $T_{\text{opt}}$) were set according to the standard parameters of the STICS model (See Brisson et al., 1998; http://www.avignon.inra.fr/agrocilm_stics/). Thus the minimal, optimal and maximal temperatures for winter wheat growth were set to 0, 20 and 37°C, respectively; the polynomial degree ($\beta$) of the temperature-stress-function $F_T$ was set as described by Duchemin et al. (2008); and the constant $Y_G$ was fixed at 0.74, which is the average of three values for winter wheat given by Amthor (1989).

2.1.5.2. Parameters from in situ data

This group includes the light-interception coefficient ($K_{\text{ext}}$), the corrective factor over the GPP during senescence ($C_i$), the harvest index (HI), the straw export coefficient (sc), the root fraction parameters ($fr_0$, $fr_\infty$ and c), the carbon content coefficient ($C_{\text{veg}}$), the conversion factor of $T_a$ into $T_s$ ($t$) and the parameter related to the fELUE function ($b$).
These parameters are fixed exclusively based on our Auradé and Lamasquère situ measurements (Béziat et al., 2009) without regard for the SAFY-CO2 module. The $K_{ext}$ was computed by inverting Beer’s law and by using the fractions of absorbed photosynthetically active radiation (FAPAR) and LAI, which were both obtained from hemispherical photographs taken over the crops (at different growth stages). A value of $K_{ext}=0.76$ was found for winter wheat (Veloso, 2014). The HI was fixed by plotting the destructive biomass against yield measurements (performed over 16 fields over the French study area; see Veloso, 2014). A HI equal to 0.45±0.05 was obtained, and the corrective factor $C_s$ was empirically fixed at 1.2. The $sc$ parameter was estimated according to Eq.(20) from the in situ grain yield, total aboveground biomass and exported straw biomass data at the Lamasquère site.

The root fraction related parameters were initially set according to Baret’s results ($fr_0=0.6$, $fr_\infty=0.1$ and $c=1.5$) and were slightly modified as described by (Béziat, 2009) to better fit with our study sites according to the measurements performed at the experimental sites. The parameters were fixed to $fr_0=0.63$, $fr_\infty=0.11$ and $c=1.48$ and the $C_{veg}$ coefficient was set to 0.46 gC/g$veg$, (Béziat, 2009).

Analyses of the air and soil surface temperature data measured by our meteorological towers at the experimental sites throughout the year (including vegetative and bare soil periods) from 2006 until 2010 indicated a linear correlation ($R^2 = 0.92$) with a slope of 1.07, which was used to estimate $T_s$ from $T_a$ (Veloso, 2014). To estimate parameters $a$ and $b$ for the effective light-use efficiency function ($fELUE$, Eq. (4)), field data from the radiation sensors mounted on our experimental sites were used. The relationship between RUE and $Rdf/Rg$ was defined at 5 European cropflux site as an exponential function, with parameter $b=1.37$ and a determination coefficient of $R^2=0.63$.

2.1.5.3. Parameters calibrated from remote sensing data

The third class of parameters includes the parameters that were calibrated using an iterative method based on minimizing the Root Mean Square Error (RMSE) between the remotely sensed BV-NET LAI time series and the time series estimated by the SAFY-CO2 module.

These parameters include the ELUE and the phenological parameters, the plant emergence day ($D_0$), the specific leaf area (SLA), the two parameters of the partition-to-leave function ($P_{La}$ and $P_{Lb}$), and the two parameters of the senescence function (sum of temperature for senescence (STT) and rate of senescence (Rs)).

The minimization procedure is based on an adapted version of the Nelder-Mead simplex method (Lagarias et al., 1998), that considers a priori boundaries for each parameter in order to constrain the solutions within realistic parameter intervals. To reduce the probability of local minima, a global approach is applied which runs the optimization process 30 times, with different a priori conditions for each parameter. The set of parameters with the best solution is considered (i.e., lower RMSE for the LAI estimates). The number optimization runs is set to 30, based on a sensibility analysis, so that the best combination of parameters can always be retrieved while avoiding unnecessary runs.

At first, the boundaries of the parameters are estimated based on a literature review. Then a sensitivity analysis of the model is conducted to adjust these boundaries for several cultural years, using a grid-search. The ranges of the parameters are discretized and all possible combinations are simulated (more than 3 million simulations). The outputs are then compared to the outputs obtained
by optimizations performed using the adapted simplex method described above and the same parameter boundaries. This comparison allows us to do the following.

1- Verify that the adjusted boundaries could reproduce all plant development conditions, with the constraint of a limited dispersion in the outputs.

2- Validate the efficiency of the adapted version of the simplex in retrieving the best set of parameters.

The minimization procedure was based on an adapted version of the Nelder-Mead simplex method.

Finally, the calibration procedure was completely based on the satellite-derived LAI time series. Therefore, no in situ data concerning the net CO\textsubscript{2} fluxes or biomass/yield were used in this step.

### 2.2. The soil module

#### 2.2.1. Description

The soil water availability refers to the capacity of a soil to retain some water available to plants and evaporation. The water capacities of the evaporative layer (TEW), of the root compartment (TAW) and of the deep compartment (TDW) are given by the equations (21), (22) and (23); besides, they depend upon the effective depth of the surface, root and deep soil layers (Z\textsubscript{e}, Z\textsubscript{r} and Z\textsubscript{d}, respectively).

After heavy rainfall or irrigation, the soil will drain until field capacity is reached. Field capacity (θ\textsubscript{fc}) is the amount of water that a well-drained soil should hold against gravitational forces, or the amount of water remaining when downward drainage has markedly decreased (Allen et al., 1998). In the absence of water supply, the water content in the root zone decreases as a result of water uptake by the crop. As water uptake progresses, the remaining water is held to the soil particles with greater force, lowering its potential energy and making it more difficult for the plant to extract it. The water uptake becomes zero when the wilting point is reached. Wilting point (θ\textsubscript{wc}) is the water content at which plants will permanently wilt. As the water content above field capacity cannot be held against the forces of gravity and will drain and as the water content below wilting point cannot be extracted by plant roots, the total available water in each soil layer is the difference between the water content at field capacity and the wilting point (in m\textsuperscript{3}.m\textsuperscript{-3}), weighted by the effective layer depth (in mm).

The water currently contained in the three soil layer is represented by the variables named AEW, AAW, ADW, for the surface, root and deep soil layers, respectively. The update of the current water content of to superficial layer (AEW, Eq.(24)) depends upon the daily effective precipitation and irrigation (PE), the daily evaporation (E) and transpiration (T.fts). The fraction of water that is taken from the superficial layer for transpiration (fts, Eq. (25)) refers to the ratio between the actual water content of the superficial layer (AEW) and the total actual water content of the two first reservoirs (superficial and root). The effective precipitation and irrigation (PE, Eq. (26)) are a fraction of the daily cumulated rain (P) and irrigation (I), which are function of the fraction of soil surface that is effectively exposed to evaporative energy (1-Fcover), and that is limited by the evaporative demand (represented by the reference evapotranspiration ET\textsubscript{a}).
According to the dual-crop coefficient theory (Allen et al., 1998), during the crop development, the soil evaporation (E, Eq. (27)) is function of ET₀ and of a soil water evaporation coefficient (Ke). This coefficient is function of the surface that is not covered by the vegetation (1-Fcover) and of the superficial relative humidity (He). He [Eq. (38)] is defined as the ratio between the available evaporable water (AEW) and the total evaporable water (TEW). Besides, during dry extreme episodes, the evaporation is limited by a β function, which approximates a bilinear behavior, as established in Allen et al., (1998). However, in order to calculate accurate annual water budgets, the original soil evaporation function had to be modified for intercropping periods (i.e. when soil is bare). Indeed, the FAO-56 method estimates the evaporative demand considering an ET₀ that is calculated in reference of a 12 cm high grassland. This reference is not adapted for bare soil conditions. Therefore, following Soarès et al. (1988) we applied a corrective function over ET₀ and evaporation was calculated as presented in Eq. 28 for bare soil periods.

The transpiration (T, Eq. (29)) is determined by the product of the reference evapotranspiration ET₀ by a basal crop coefficient (Kcb). Moreover, the plant transpiration is reduced by the water stress coefficient (Ks), when stress conditions are met. The water stress function is described by Allen et al., (1998). Ks is a bilinear function, ranging between 0 (when the vegetation is completely stressed) and 1 (no water stress), and depending upon a critical relative humidity parameter (Hcrit) and the soil maximal relative humidity (He or Hr).

Through the vegetative period, the root layer is limited by the root effective depth (Zr, Eq. (31), expressed in m). The Zr evolves during the season as a function of the root growth speed (Vpr), which is modulated by the air temperature (Ta) and the water stress coefficient (Ks).

The update of the available water content of the root layer (AAW, Eq.(24) (32)) depends upon the fraction of the transpiration not extracted of the superficial layer (1-fts) and on the excess of water drained of the superficial zone (the depletion term DPₑ). In this way, for each compartment, the total available water is split into the water currently contained in the soil (AEW, AAW, ADW) and the complementary empty space or depletion (DPₑ, DPᵣ, DP₉, Eqs. (35), (36), (37)). When all compartments are full, the excess water flows out of the system as deep drainage. The deep soil layer refers to a water storage reservoir.

The deep available water (ADW, Eq. (33) or (34)) is thus connected to the root or the superficial layer, depending on the presence of vegetation or not. Finally, the deep water excess (DPₑ) is definitely lost for the soil-plant system.

Water diffusion due to capillarity water movement, either upwards or downwards, is modeled between the superficial, root and deep compartments (or only superficial and deep out of vegetative periods) on the basis of their relative water content. It means the diffusive flux between adjacent layers is based on the moisture gradient between the two layers. The diffusive fluxes (φₓᵧ, Eqs. (39)(40)(41)) are calculated based on the method proposed by Devonec and Barros (2002), and used by Duchemin et al., (2005), for which the relative moisture gradient (θₓ-θᵧ) is normalized by the soil field capacity (θₑ).
\[
T_{EW} = \left( \theta_{rc} - \frac{\theta_{wp}}{2} \right) \cdot Z_{e} \cdot 1000
\]  
\[T_{AW} = \left( \theta_{rc} - \theta_{wp} \right) \cdot Z_{r} \cdot 1000 \]  
\[T_{DW} = \left( \theta_{rc} - \theta_{wp} \right) \cdot Z_{d} \cdot 1000 \]

\[A_{EW} (i) - A_{EW} (i - 1) + P_{E} (i) - E (i) - T (i) \cdot f_{is} \] 
\[f_{is} = \frac{A_{EW}}{A_{EW} + A_{AW}} \]

\[P_{E} = \max \left\{ \left\{ (P + I) - \min \left\{ (P + I) \times (1 - F_{cover}), E_{T0} \right\}, 0 \right\} \right\} \]

\[E = (1 - F_{cover}) \cdot E_{T0} \left( \frac{(1 - (1 - H_{e})^\beta)}{\kappa} \right) \]

\[E = E_{T0} \times \left( -0.17 \times E_{T0} + 1.45 \right) \times \left( \frac{S_{M} - \theta_{wp}}{\theta_{fc} - \theta_{wp}} \right) \]

\[T = K_{cb} \cdot K_{s} \cdot E_{T0} \]

\[K_{s} = \min \left\{ 1 - \frac{H_{Rs} - H_{crit}}{H_{crit} - H_{R}}, 1 \right\} \]

\[H_{Rs} = \max \{H_{e}, H_{r}\} \]


\[ Z_r (j) = \max \{ Z_r (j - 1) + Ta_r (j) \times K_s (j) \times V_{pr}, Z_r - Z_v \} \]  \hspace{1cm} (31)

\[ AAW (i) = AAW (i - 1) + DP_e - T (i) \times (1 - f_{is}) \]  \hspace{1cm} (32)

\[ ADW (i) = ADW (i - 1) + DP_v \]  \hspace{1cm} (33)

\[ ADW (i) = ADW (i - 1) + DP_e \]  \hspace{1cm} (34)

\[ DP_e = \max \{ TEW - AEW, 0 \} \]  \hspace{1cm} (35)

\[ DP_v = \max \{ TAW - AAW, 0 \} \]  \hspace{1cm} (36)

\[ DP_d = \max \{ TDW - ADW, 0 \} \]  \hspace{1cm} (37)

\[ He = \frac{AEW}{TEW}; Hr = \frac{AAW}{TAW}; Hd = \frac{ADW}{TDW} \]  \hspace{1cm} (38)

\[ \Phi_{13} = K_{dif} \times \left( \frac{\theta_1 - \theta_2}{\theta_{fc}} \right)^{E_{dif}} \]  \hspace{1cm} (39)

\[ \Phi_{12} = K_{dif} \times \left( \frac{\theta_1 - \theta_2}{\theta_{fc}} \right)^{E_{dif}} \]  \hspace{1cm} (40)

\[ \Phi_{23} = K_{dif} \times \left( \frac{\theta_2 - \theta_3}{\theta_{fc}} \right)^{E_{dif}} \]  \hspace{1cm} (41)
2.2.2. Coupling SAFY-CO2 with the water module

SAFY-CO2 is a model resulting from the coupling between SAFY-CO2 model (Veloso, 2014), representing the vegetation module, with the water budget module, presented in the previous paragraph. This coupling is achieved by means of three main variables (at daily step): the LAI, the water stress (Ks) and the superficial soil moisture (He).

The water stress Ks calculated by the water module is taken into account in the photosynthesis estimation [Eq. (1)], limiting the GPP when water stress conditions are met. The photosynthesis estimation could already be impacted by temperature stresses (by means of the F(Ta) function); but all the others stresses (water, nitrogen, ...) were “included”, in some way, in the light-use efficiency term (fELUE). The introduction of the water stress function allows better accounting of the effects of water stress episodes over the crop production; the Ks is therefore decoupled from the fELUE.

In addition, the LAi variable, simulated by the vegetation modules, is primarily used for the estimation of the vegetation cover fraction (Fcover, Eq. (42)). Fcover is estimated according to the method presented by Welles and Norman, (1991), for which the Fcover is a function of the LAI, of the total plant area index (Al), and of two empirical coefficients (Kcov and Ecov). However, for the sake of simplicity, and given that the model is not capable of specifically simulating the total plant area, we consider the term LAI equals to AI, which makes the term [LAI + AI / 2 x AI] negligible. The Fcover term participates to the estimation of the effective intercepted rain and irrigation (PE) and to the evaporation estimates.

The (vegetation module) LAI is also used for the crop transpiration estimates, by means of the crop basal coefficient (Kcb). Therefore, the Kcb [Eq. (43)] is calculated according to a function of the LAI and of two other coefficients: the Kcbmax and the Etrp.

\[ F_{cover} = K_{cov} \times (1 - e^{-E_{cov} \times LAI}) \times \left[ \frac{LAI + AI}{2 \times AI} \right] \]  \hspace{1cm} (42)

\[ Kcb = K_{cbmax} \times (1 - e^{-E_{trp} \times LAI}) \]  \hspace{1cm} (43)

The last difference in the SAFYE-CO2 model relative to SAFY-CO2 consists in the heterotrophic respiration (Rh) estimation. For SAFY-CO2, Rh was calculated using an empirical exponential equation depending exclusively on the soil temperature (Ts). With the inclusion of the water module, SAFYE-CO2 is capable of simulating the evolution of the superficial soil humidity. Therefore, a new Rh function is implemented, depending on both soil temperature and soil moisture estimates [Eq. (44)]. This equation’s formalism is based on that present in the CENTURY model (Parton et al., 1987), which was used (and calibrated) by Delogu (2013). The parameters Rhbase and Q10 were calibrated using the NEE and SWC data from the flux towers (Auradé and Lamasquère), from 2006 to 2010, over periods of bare soil. The Q10 is set to be equal to 2.3. The parameter Rhbase corresponds to a reference Rh at a chosen temperature. A different value was set for each site. Table 2 presents the adjusted parameters (and associated statistical indicators R and RMSE) found for both sites. For the other fields within our study area extent, a mean value of Rhbase=0.49 is used, and Q10 remains fixed to 2.3.
Table 2. Heterotrophic respiration ($R_h$) parameters (extracted from Delogu, 2013). The $R_{hbase}$ and RMSE units are gC.m$^{-2}$.day$^{-1}$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Auradé</th>
<th>Lamasquère</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{h base}$</td>
<td>0.45</td>
<td>0.52</td>
</tr>
<tr>
<td>$Q_{10}$</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>RMSE (StD)</td>
<td>0.64</td>
<td>0.20</td>
</tr>
<tr>
<td>R (StD)</td>
<td>0.68</td>
<td>0.52</td>
</tr>
</tbody>
</table>

The SAFYE-CO2 soil module presents 13 new parameters, which are listed in Table 1. These parameters can be related to the soil processes or to the vegetation processes. Besides, they can be fixed in different ways: i) according to values found in the literature; ii) according to in-situ measurements/observation; iii) by means of a calibration process.

### 2.2.3. Soil module parametrization and calibration

#### 2.2.3.1. Parameters from the literature and from in-situ measurements

This category of parameters can be divided into the soil ($\theta_{fc}$, $\theta_{wp}$, $Z_e$, $Z_d$) and vegetation ($K_{cov}$, $E_{cov}$ and $H_{crit}$) related parameters.

The soil intrinsic properties are characterized by means of the following parameters: the soil field capacity ($\theta_{fc}$) and wilting point ($\theta_{wp}$), the soil depth ($Z_d$) and the soil superficial layer depth ($Z_e$).

The $Z_e$ determines the water volume that can be assigned to evaporation. It was set to 5 cm, according to the value found in models of the literature, like ISBA (Noilhan and Planton, 1989) and ICARE (Gentine et al., 2007). The three other parameters ($\theta_{fc}$, $\theta_{wp}$, $Z_d$) are field-specific, varying spatially and depending upon the soil type. For the experimental sites (Auradé and Lamasquère) these values were obtained from in-situ measurements and soil analysis. The values are listed in Table 4. The Lamasquère site is characterized by a clay and deep soil (around 2m), presenting a large capacity of water storage. The Auradé soil presents a high spatial variability and a lower average depth (between 0.6 and 1.5m). Besides, its texture properties ($\theta_{fc}$, $\theta_{wp}$) yield to an inferior capacity of total water content.
Table 3. Soil hydraulic characteristics of the Auradé and Lamasquère sites.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Auradé</th>
<th>Lamasquère</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field capacity ((\theta_{fc}), m(^3).m(^{-3}))</td>
<td>0.35</td>
<td>0.46</td>
</tr>
<tr>
<td>Wilting point ((\theta_{wp}), m(^3).m(^{-3}))</td>
<td>0.17</td>
<td>0.26</td>
</tr>
<tr>
<td>Soil deep layer maximal depth ((Z_d), m)</td>
<td>1.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

For the other fields within our study area, the given parameters are estimated from a regional soil map (see Veloso, 2014). The parameters \(\theta_{fc}\) and \(\theta_{wp}\) are extrapolated from the soil clay content maps, according to a relationship established over a number of field measurements (see Veloso, 2014). The vegetation parameters related to the vegetation cover fraction estimation (Fcover) are the \(K_{cov}\) and \(E_{cov}\) coefficients. They were set by fitting an exponential law relating the GAI and Fcover, both obtained from hemispherical photographs taken over wheat crops (at developed growth stage, when GAI=Al) and processed using the CAN-EYE software (See Veloso, 2014). Values of \(K_{cov}=0.91\) and \(E_{cov}=0.31\) were found by minimizing the root mean square error between the established law and the measured data. These values are relatively close to those reported by Duchemin et al., (2006) for irrigated winter wheat in Morocco (\(K_{cov}=0.95\) and \(E_{cov}=0.53\)).

Finally, the transpiration reduction coefficient (\(H_{crit}\)) that represents the critical humidity for activating the plant water stress for transpiration is set constant for all the winter wheat fields. \(H_{crit}\) is fixed according to the value reported by Allen et al., (1998), for which \(H_{crit}=0.55\).

2.2.3.2. **Calibrated parameters**

The SAFYE-CO2 water module parameters that were fixed through a calibration approach are: the parameter related to the plant root growth rate (Vpr), the parameters related to the transpiration estimates (\(K_{cbmax}\) and \(E_{trp}\)), the parameter related to the soil evaporation (\(\beta\)) and finally the parameter concerning the diffusive fluxes (\(K_{dif}\) and \(E_{dif}\)). They were calibrated in the chronological order for which they are cited in the text.

The parameters calibration methodology is based upon evapotranspiration (ETR) and soil water content (SWC) data measured over the experimental sites. Five site-years of data were used: AUR2006, LAM2007, AUR2008, LAM2009 and AUR2010.

The calibration approach consists in using the ETR and SWC data of two site-years for calibrating the six cited parameters (Vpr, \(K_{cbmax}\), \(E_{trp}\), \(\beta\), \(K_{dif}\) and \(E_{dif}\)) and the data of the resting three site-years for validation. In order to choose the best pair of years for calibrating the parameters, all the combinations were tested (a total of 10 possibilities). The cost function used in the parameter’s optimization is calculated from the sum of relative errors (RRMSE) between the model estimated and the measured ETR (or SWC) for the two selected years. The optimization process searches the set of parameters that minimizes the dual cost function.

The simplex method, with restricted parameters values boundaries, is chosen as optimization approach. The optimization of the parameters is performed through four sequential steps: 1) Vpr; 2)
Kcb\(_{\text{max}}\) and E\(_{\text{trp}}\); 3) \(\beta\); 4) \(K_{\text{dif}}\) and \(E_{\text{dif}}\). These six parameters are fixed to values found in the literature, as a start point value for the optimization.

The first step aims at calibrating the root growth rate parameter (Vpr). The initial value of Vpr is set as 0.0012 m.°C, according to the STICS model parameterization for the winter wheat crop. For setting the interval within the optimal Vpr is searched, we set a threshold of ±40% around the start value; i.e the optimal Vpr must be included in the range of [0.00072-.0017]. Through this step, the resting parameters remain constant.

The second step is dedicated to the optimization of the parameters related to transpiration: Kcb\(_{\text{max}}\) and E\(_{\text{trp}}\) (which define Kcb, Eq.(43)). The initial values for these two parameters were set according to in-situ measurements. The basal crop coefficient Kcb can be defined as the ratio of ETR to ET\(_0\) when the soil surface layer is dry but when the average soil water content of the rootzone is adequate to sustain full plant transpiration. Figure 2 illustrates the relationship between Kcb and LAI, established from ETR fluxes measured by the flux towers and from destructive measurements of LAI performed at the Auradé and Lamasquère sites. The ETR data were filtered according to two criteria: i) no water supply (precipitation) was observed during a period of 4 days, in order to reduce the influence of soil evaporation; ii) no observed vegetation stress, based on a minimum threshold of soil root water content superior to 0.65 of the field capacity \(\theta_{\text{fc}}\). The LAI data were interpolated to fit the Kcb data. From this relationship, we obtain Kcb\(_{\text{max}}\) =1.07 and E\(_{\text{trp}}\) = 1.25. These values are set as starting points for the optimization process.

Besides, for Kcb\(_{\text{max}}\) we set a minimum–maximum interval of [0.6 -1.15] according to Allen et al., (1998) and to field expertise. The optimization interval for E\(_{\text{trp}}\) is empirically set to [0.2 - 1.72].

![Figure 2. LAI-Kcb relationship. The crop coefficients Kcb are computed as the ratio of actual and reference evapotranspiration (ETR/ET\(_0\), y-axis). The obtained coefficients of the exponential relationship, linking Kcb and LAI, are displayed.](image)
The third step of the calibration procedure concerns the \( \beta \) parameter, related to the evaporation stress function estimate. Therefore, for this step the cost function is based on the integration of the errors (RRMSE) relative to ETR and also to superficial SWC between measurements and estimates. The initial value of \( \beta \) is set to an average value found by Claverie (2012) through a calibration procedure using data from Lamasquère (2006) and Auradé (2007). The interval for optimization was set to \( \beta \) within \([0.3-1.5]\), according to empirical tests performed over the whole data set (from 2006 to 2010).

The fourth, and last, step of the calibration process aims at setting the parameter related to the diffusive fluxes estimation: \( K_{\text{dif}} \) and \( E_{\text{dif}} \). The calibration of these parameters is important for the soil water content estimations but also for the simulation of the evapotranspiration. These parameters can be very different, depending on the soil properties. Devonec and Barros (2002) have found optimal values of \( K_{\text{dif}} = 0.27 \) and \( E_{\text{dif}} = 1 \); meanwhile Duchemin et al. (2005) found quite higher values: \( K_{\text{dif}} = 175.15 \) and \( E_{\text{dif}} = 3.18 \). For our study area, Claverie (2012) has determined \( K_{\text{dif}} = 3.5 \) and \( E_{\text{dif}} = 1 \). We use these last values as starting points for the optimization process. Given the large extension of the reported values for setting \( K_{\text{dif}} \) and \( E_{\text{dif}} \), we decide to state an extremely large interval for this optimization of \([0-500]\) for both parameters (to give a high degree of freedom and avoid negative solutions).

Therefore, this 4-steps optimization procedure was applied for each of the ten possible combinations of two years used for the parameters calibration. Each set of obtained calibrated parameters (\( V_{\text{pr}} \), \( K_{\text{cb max}} \), \( E_{\text{trp}} \), \( \beta \), \( K_{\text{dif}} \) and \( E_{\text{dif}} \)) was then applied to the three years validation data sets. The resulting evapotranspiration and superficial soil water content estimates for three validation-years were compared against the in-situ measurements. The error (RMSE) and the Nash-criteria were calculated for each case, and are displayed in Table 5. According to these results, which are differentiated by a color code: from the worst, in red, to the best results, in green, we observe that the pair of years 2007 (LAM) and 2008 (AUR) yields to good results in terms of both ETR and top-layer SWC. As a consequence, we choose these two site-years as the calibration sets and the other site-years (2006, 2009, 2010) constitute the validation data set.

The set of calibrated parameters are: \( V_{\text{pr}} = 0.0072 \), \( K_{\text{cb max}} = 0.98 \), \( E_{\text{trp}} = 0.36 \), \( \beta = 0.48 \), \( K_{\text{dif}} = 1.06 \) and \( E_{\text{dif}} = 6.38 \). They were fixed to these values for all the investigated fields within our study area (including the experimental sites), regardless the year (from 2006 to 2011).
Table 4. Performances of the parameters optimization. A set of five site-years was available: AUR2006, LAM2007, AUR2008, LAM2009, AUR2010. The first column indicates the years used for calibrating the parameters (Vpr, Kc,max, Etrp, β, Kdiff and Ediff). The performances (RMSE and Nash-efficiency Eff) were calculated using the three remaining years for the evapotranspiration (ETR) and the superficial soil water content (SWC). For each column (2 to 5) the values are classed from the worst (in red) to the best (in green). The performances for the pair of years selected as the best one (Y2007_2008) are highlighted.

<table>
<thead>
<tr>
<th>Calibration Years</th>
<th>RMSE ETR</th>
<th>Eff ETR</th>
<th>RMSE SWC</th>
<th>Eff SWC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y2006_2007</td>
<td>0.64</td>
<td>0.34</td>
<td>0.04</td>
<td>0.54</td>
</tr>
<tr>
<td>Y2006_2008</td>
<td>0.55</td>
<td>0.61</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>Y2006_2009</td>
<td>0.54</td>
<td>0.61</td>
<td>0.06</td>
<td>0.14</td>
</tr>
<tr>
<td>Y2006_2010</td>
<td>0.50</td>
<td>0.67</td>
<td>0.07</td>
<td>-0.24</td>
</tr>
<tr>
<td>Y2007_2008</td>
<td>0.48</td>
<td>0.66</td>
<td>0.05</td>
<td>0.33</td>
</tr>
<tr>
<td>Y2007_2009</td>
<td>0.50</td>
<td>0.59</td>
<td>0.05</td>
<td>-0.20</td>
</tr>
<tr>
<td>Y2007_2010</td>
<td>0.51</td>
<td>0.62</td>
<td>0.05</td>
<td>0.09</td>
</tr>
<tr>
<td>Y2008_2009</td>
<td>0.51</td>
<td>0.66</td>
<td>0.06</td>
<td>-0.11</td>
</tr>
<tr>
<td>Y2008_2010</td>
<td>0.55</td>
<td>0.63</td>
<td>0.07</td>
<td>-0.38</td>
</tr>
<tr>
<td>Y2009_2010</td>
<td>0.56</td>
<td>0.58</td>
<td>0.07</td>
<td>-0.36</td>
</tr>
</tbody>
</table>

3. Model validation

Validation of the simulated soil water content (SWC), evapotranspiration (ETR) and CO₂ fluxes (GPP, ecosystem respiration (Reco), NEE) will be performed against soil moisture sensor (CS616, Campbell Scientific Inc, Logan, UT, USA) and against eddy-covariance flux measurements (Aubinet et al., 1999; Baldocchi, 2003) that were carried out since 2005 over the Auradé and Lamasquère ICOS flux sites (Béziat, 2009) included in the French study area (OSR, Regional Space Observatory). They are both part of the ICOS ERIC network (https://www.icos-cp.eu/) for measuring ecosystem’s greenhouse gases emissions. The EdiRe software (Robert Clement, c 1999, University of Edinburgh, UK) was used to calculate fluxes. Flux filtering, quality controls, gap filling, NEE partitioning into gross primary production (GPP) and ecosystem respiration (Reco) components were performed following the CarboEurope-IP recommendations (Beziat et al., 2009). At Auradé, the crop rotation is winter wheat-sunflower-winter wheat-rape, the plot is not irrigated, only grain is exported and only mineral fertilisers are applied. At Lamasquère, the crop rotation is winter wheat-maize for silage, the plot is irrigated when maize is grown, both grain and straw are exported and both organic and mineral fertilisers are applied (for a complete description of the sites see Béziat et al., 2009).

Crop production (biomass and final grain yield) will be evaluated against in situ measurements (from the two flux sites and from samples collected during field campaigns). Détails concerning protocols of biomass sampling and yield estimates during the SENSAGRI field campaign are listed in SENSAGRI deliverable D7.3. Protocols concerning collection of ground truth for LAI, biomass and yield validation over the French site during previous years are described in Veloso (2014).
Apart from the core European test sites (France, Spain and Italy) the model could be tested against ground-truth data coming from agricultural sites outside Europe. In this respect, the SENSAGRI consortium partners’ Pan-European and global dissemination network will be utilized for obtaining access to agricultural sites across the world, e.g. as part of the JECAM network (http://www.jecam.org/) which gather 34 sites located in all the continents or as part of the ICOS and FLUXNET networks gathering experimental plots equipped with eddy-covariance flux stations.

4. Performance of the model for winter wheat

4.1. LAI and Biomass

Results presented here below concern winter wheat only. The results for Sunflower and maize are presented in the Supplementals. Phenological parameters of the SAFYE-CO2 plant module and LUE were calibrated using LAI maps produced from S2 like optical data in 2011 (SPOT 4 and 5, Formosat-2) over the OSR area. Figures 3 and 4 illustrate the scatter plots of observations against SAFYE-CO2 estimates of LAI and biomass, respectively, for the Auradé and Lamasquère ICOS experimental sites and for the fields from the 2011 field campaign that was carried out over the OSR area (with a biomass sampling protocol similar to the SENSAGRI campaign).

The analysis of these figures reveals that the SAFY-CO2 model provides accurate estimates of the LAI, with RRMSE of 11.8% and R²=0.98, and of the biomass as well, with RRMSE of 25.9% and R²=0.89. However, the satellite derived LAI in this figure tends to be underestimated compared to the one measured by means of destructive sampling on the field (data not shown). As a consequence, high values of biomass are underestimated by the model because remote sensing derived LAI are underestimated too. It is important to note that the coupling of the SAFY-CO2 module with the soil module did not affect much the performances of the model for LAI, biomass and yield estimates. However, for LAM2011, we note a marked underestimation of the final biomass, that was already present for SAFY-CO2, but accentuated by the SAFYE-CO2 version due to the effect of water stress. For the other years, (2006-2010) the results are essentially the same (since no water stress occurred, except during the senescence phase in 2006). The performances of the SAFY, SAFY-CO2 and SAFYE-CO2 versions of the model are presented in Figure 5. In Sensagri, the combined use or S1 data together with S2 data may reduce the underestimation of LAI derived from remote sensing and as a consequence biomass estimates could be improved.
Figure 3. Comparison between the LAI simulated by the SAFY-CO2 model and the satellite-derived LAI (observation) for the experimental sites of Auradé and Lamasquère (represented by the x symbol) and for the fields from the 2011 campaign (represented by the diamond symbol). The line 1x1 is displayed. The performances (RMSE, RRMSE, Bias and R²) are indicated on the right corner.

Figure 4. Comparison between biomass simulated by the SAFY-CO2 model and ground measurements for the Auradé and Lamasquère sites (represented by the x symbol) and for the fields from the 2011 campaign (represented by the diamond symbol). The line 1x1 is displayed. The performances (RMSE, RRMSE, Bias and R²) are indicated on the right corner.
4.2. Yield

Figure 6 shows that different strategies for validating the modeled yield can be used but that the classical approach based on yield data provided by the farmers (Figure 6b) are not effective. Indeed, the range of yields is too narrow to allow an appropriate validation. The reason is that data provided by the farmers are usually mean of the yield over several plots which reduces the range of observed data. The method that produces more accurate validation of the model is based on manual vegetation sampling just before harvest in heterogeneous fields (Figure 6a). This approach that allows to catch the true variability of yield in the fields shows that the SAFY-CO2 model provides good estimates of the yield, with RRMSE of 25.7% and $R^2=0.83$. Unfortunately, this approach is very time consuming. For this reason, in the future, we'll put more effort on the last approach that uses yield maps produced from combined harvesters. However, as in the example shown in Figure 6c, it often happens that the yield sensor of the combined harvester is not properly calibrated. Therefore those yield maps must be combined with yield data provided by the farmer to correct the slope of the relationship between observations and the model output. Once done, the dataset allows to catch the yield spatial variability at plot scale and is unbiased.
4.3. Components of the net CO$_2$ fluxes

4.3.1. GPP

The dynamics of simulated gross primary production (GPP) for winter wheat were compared to the in-situ GPP data. Figure 7a) and b) present the observed GPP for the crop season 2005-2006 and the simulated ones with SAFY-CO$_2$ and SAFYE-CO$_2$. We observed that the estimated GPP dynamics are in agreement with the measured ones (Figure 7a and 7b)), presenting a correlation coefficient around 0.9 and a RMSE about 1.4 gC m$^{-2}$d$^{-1}$ for both versions of the model. The dynamics of GPP are very close to those of LAI. Also, regardless the year, we note that the growing period estimates, approximately until early May, match well with the observations. However, a slight deviation is observed through the senescent phases at Auradé in 2006 and form the scatter plots (on the right), we observed an overall overestimation of the GPP estimates, especially for the high GPP values.
Figure 7. a) Evolution of the GPP for the Auradé site 2005-2006 winter wheat crop season with the previous version of the model (SAFY-CO2), b), c) and d) evolution of the carbon fluxes (GPP, Reco, NEE respectively) for the Auradé site 2005-2006 winter wheat crop season with the new version of the model (SAFYE-CO2). Observed fluxes are represented in black and simulated fluxes in blue. On the right the scatter plots relating observed vs. simulated variables and associated statistics (regression, RMSE and $R^2$) are displayed.
When analyzing the GPP daily dynamics, it can be noted that this overestimation mainly occurs from maximum development period until the mid senescence. When compared with the SAFY-CO2 GPP estimates, we observe that this overestimation was already noticeable, and it was stronger than with SAFYE-CO2.

As it can be seen in Figure 8 illustrating the water stress function in SAFYE-CO2, for AUR2006, the water stress started in May and ended in June. The water stress function is comprised between 0 and 1. The lower this function is, the more stressed is the vegetation. It means that for this period, the GPP estimates were reduced by the water stress with SAFYE-CO2 (Figure 7b), getting the estimates closer to the observed ones than with SAFY-CO2 (Figure 7a).

![Figure 8. Water stress function simulated by the SAYE-CO2 model for Auradé 2006 (on the left) and Lamasquère 2007 (on the right). The water stress is comprised between 0 (maximal stress) and 1 (no stress). The precipitations measured at our sites are displayed in the right Y-axis.](image)

For the other years (2007-2010), the crops were not affected by some water stress but the results from AUR2006 show the importance of considering possible water stress over the flux estimates. Finally, we note that the effect of crop re-growth and weed development increase GPP from mid-August until late September (see red frame in Figure 7a). Those events were accounted for in the simulations with SAFY-CO2 (Figure 7a) but not with SAFYE-CO2 (Figure 7b).

Table 6 summarizes the obtained performances with SAFYE-CO2, in terms of correlation ($R^2$) and root mean square error (RMSE) for the cropping seasons 2005-2006 till 2009-2010. In terms of absolute observed GPP values, the 2007 and 2010 crop seasonal dynamics present higher values than the others years (not shown). For these years, despite the good correlation between observations and estimates ($R^2=0.94$), the GPP estimates are underestimated by the model through the whole growth development period (for more details, see Veloso (2014)).
Table 5. Performances of the CO$_2$ flux components estimated by the SAFYE-CO2 model for winter wheat over the Auradé (AUR) and Lamasquère (LAM) sites, from 2006 to 2010. For comparison, the performances obtained by the SAFY-CO2 model are indicated on the left side of each field, in grey color.

<table>
<thead>
<tr>
<th></th>
<th>GPP</th>
<th>Reco</th>
<th>NEE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R^2$</td>
<td>RMSE*</td>
<td>$R^2$</td>
</tr>
<tr>
<td>AUR2006</td>
<td>0.91/0.92</td>
<td>1.42/1.36</td>
<td>0.77/0.77</td>
</tr>
<tr>
<td>LAM2007</td>
<td>0.94</td>
<td>1.4</td>
<td>0.80/0.81</td>
</tr>
<tr>
<td>AUR2008</td>
<td>0.94</td>
<td>1.26</td>
<td>0.74/0.75</td>
</tr>
<tr>
<td>LAM2009</td>
<td>0.93</td>
<td>1.13</td>
<td>0.71/0.75</td>
</tr>
<tr>
<td>AUR2010</td>
<td>0.94</td>
<td>1.27</td>
<td>0.82/0.85</td>
</tr>
</tbody>
</table>

* RMSE in gC m$^{-2}$ d$^{-1}$.

4.3.2. Reco

Overall, we observe that the ecosystem respiration (Reco) follows the same dynamics as GPP, but in an attenuated way; i.e., differences between bare soil and vegetative periods are smaller. In general, simulated Reco matches well with observations (Figure 6c). In 2007, however (and to a lesser extend in 2008 and 2010), after maximum growth development, the estimates seem to diverge from the observations (not shown). For Lamasquère 2007 (LAM2007) we observe a poor Reco estimation, significantly underestimated in comparison to the observations. This behaviour is aberrant if compared to those of other years (see Veloso 2014 for details). That year, the vegetation had a much faster development, reaching high LAI values earlier than usual. For example, in mid-March the LAM2007 site presented a LAI of 2.5 m$^2$.m$^{-2}$, while the others siteyears had barely attained 1 m$^2$.m$^{-2}$ in the same period (not shown). The stronger Reco values in 2007 can then be explained by the fast (and strong) crop development, which can be justified by the extremely soft autumn and winter for this crop season. In the 2006-2007 season, warm temperatures were measured from the sowing (October/November) until late March. This, jointly with relatively well distributed rain events, led to an earlier development of the wheat crop. The model was not capable of reproducing this phenomenon correctly. Also, as discussed for the GPP estimates, the Reco underestimation in 2007 might be due to low satellite-LAI values assimilation, inducing here lower biomass and autotrophic respiration (Ra) estimates. Furthermore, due to the described climatic conditions, there was a strong biomass production earlier than usual in the vegetative cycle, and consequently a high mortality rate and turnover of the plant organs after tillering, phenomenon that is not taken into account by the destructive measurements of (alive) biomass. Thus, the increase of the ecosystem respiration might be due to an early decomposition process of the senescent and death plant organs.

Nevertheless, in general, the Ra simulated dynamics seem correct (except in 2007). According to the model simulations, the Ra represents the major part of the Reco during the vegetative period, which is in agreement with which was observed by Moureaux (2008) and Aubinet et al., (2009). For post-harvest periods, nevertheless, the performances can be degraded due to re-growths, weed
development or manure application/soil labor, processes that may affect the ecosystem respiration and that are not considered by the model.

Considering all years, the obtained correlation coefficients are overall satisfactory: in average, $R^2=0.79$, slightly better than with the SAFY-CO2 version ($R^2=0.78$) (see Table 6). Also, the RMSE were lower with SAFYE-CO2 (on average 0.84 gC m$^{-2}$d$^{-1}$) than with SAFY-CO2 (on average 0.93 gC m$^{-2}$d$^{-1}$). We observe that Reco performances are thus improved by SAFYE-CO2. For the non-stressed years (2007 to 2010) this improvement is entirely owed to the SAFYE-CO2 heterotrophic respiration function, which depends not only upon soil temperature (as in SAFY-CO2) but also upon soil water content (simulated by the soil module).

### 4.3.3. Net ecosystem exchange (NEE)

In general, the daily dynamics of net ecosystem exchange (NEE) are well simulated by the SAFYE-CO2 model. The average statistics indicators, calculated over the 5 site-years, indicate a correlation coefficient ($R^2$) of 0.97 and an error of 1.16 gC m$^{-2}$d$^{-1}$ (compared to 0.84 and an error of 1.16 gC m$^{-2}$d$^{-1}$ with SAFY-CO2)(see Table 6). We observe that the performances are quite similar. Still, the SAFYE-CO2 NEE estimates are slightly better correlated to in-situ measurements than those of SAFY-CO2. However, for the error (RMSE) it depends upon the year. For AUR2006, thanks to the water stress function, the GPP estimates were improved (Figure 6b). The Reco estimates were also improved due to the new Rh function of SAFYE-CO2 (Figure 6c), resulting in better NEE estimates as well (RMSE =1.12 gC m$^{-2}$d$^{-1}$) (Figure 6d). That year, the visual analysis of the simulated and observed NEE dynamics shows that they are coherent with the GPP dynamics (see Figure 6d). Also, the NEE dynamic is overall good, but the model underestimates NEE (negative values) from July till October because the GPP of the re-growth is not accounted for by the model.

On the other hand, for example, in LAM2007, the GPP estimates remained the same (no water stress), but the Reco estimates were improved by SAFYE-CO2 (RMSE =0.97 against 1.23 gC m$^{-2}$d$^{-1}$ for SAFY-CO2). Since the GPP is underestimated by both models, the improved Reco resulted in a slight “degradation” of the NEE estimates by SAFYE-CO2 (RMSE=1.16 against 1.06 gC m$^{-2}$d$^{-1}$ for SAFY-CO2). Given that the GPP and Reco terms compensate each other, higher (and better) Reco estimates highlighted the underestimation of GPP, which degraded the estimates of the NEE. Note that some effects present on NEE measurements can be either compensated or accentuated on the GPP and/or Reco calculated during the partitioning process.

Figure 9 shows the cumulated NEE values measured by the flux towers and those estimated by the SAFYE-CO2 model. They are cumulated for the period of 1st September to 31 December of the following year because it allows to encompass each cropping year entirely. The analysis of the observed cumulated NEE allows the identification of phases of CO$_2$ storage or CO$_2$ release. Here we use the micrometeorological (or atmospheric) convention, with NEE negative when the ecosystem is fixing CO$_2$ (flux moving downward) and positive when it is losing CO$_2$ (flux moving upward). A negative slope on the cumulated NEE curve means that the ecosystem behaves as a CO$_2$ sink (GPP>Reco), and a positive slope means that the ecosystem behaves as a CO$_2$ source (GPP<Reco).
From the observations, we note that the maximum absolute cumulated NEE values can be very different from one year to another as well as the time in the season at which this maximum is reached. The NEE dynamics reveal that, depending on the year, different crop developments can be noted. For AUR2006 we observe that the NEE cumulated value became negative in early April, whereas it happens a month earlier for LAM2007 (1st March), and a month later for LAM2009 and AUR2010 (around 21st April). As it was previously discussed for the GPP, in 2007 the wheat had an earlier development that year, which can also be clearly seen in the NEE cumulated values. This means that for different site-years the crop ecosystem started storing CO₂ at different times.

The 2007 and 2008 seasons are the ones that attained the higher CO₂ storage (around 526 g C·CO₂·m⁻²), in early June. For LAM2007, it is explained by the fact that the crop growth has started earlier than usual, due to the favorable climatic conditions, and thus lasted longer. In AUR2008, the wheat developed well, reaching a maximum LAI around 4 m²·m⁻². The LAM2009 season presents the lowest rate of carbon storage during the crop growth, achieving only 314 gC·m⁻² as maximum absolute NEE. Given that the emergence was low and delayed, because of the excess of water in the soil (high precipitation) during winter that year, the plants had a shorter period for assimilating CO₂ and the net assimilation was less intense due to lower plant density.

The final period of CO₂ release (positive slope on the cumulated NEE curve) is characterized by the change of sign in NEE, which becomes positive; it means that the Reco is superior to the GPP fluxes, and that the ecosystem changes from a sink to a CO₂ source. It corresponds to the senescence phase (decrease of green photosynthetic elements), passing to harvesting and then to the bare soil period.

The analysis of the profiles of cumulated NEE (Figure 9) simulated by SAFYE-CO₂ shows a good correlation with the in-situ measurements, but the errors in terms of absolute values are quite important. In general, Reco was better simulated (and less underestimated) with the SAFYE-CO₂ version than with SAFY-CO₂ (not shown). In LAM2007 and AUR2010 the apparent degradation in the modeled cumulated NEE are in reality caused by the GPP underestimation in both versions of models, but their effect is more visible on the NEE estimated by SAFYE-CO₂ (because Reco is higher and better simulated). For LAM2009 the degradation in the NEE estimates comes from a slight overestimation of the modeled Reco with SAFYE-CO₂ in December/January that leads to an underestimated cumulated NEE value in June, when senescence occurs. Then the divergence with the measurements caused by the re-growth event that is not accounted for by the model in this figure is quite visible. For AUR2008, the slight overestimation of Reco during the winter yielded to a small degradation of the cumulated NEE by SAFYE-CO₂ compared to SAFY-CO₂ (not shown). Also, during the senescence phase, GPP was underestimated by both versions of the model, but Reco was less underestimated by SAFYE-CO₂. Therefore, in June (when senescence occurs), the cumulated NEE value for the SAFYE-CO₂ version was less negative, diverging more from the observations than SAFY-CO₂ (not shown). This difference in the cumulated NEE in June between the two versions of the model leads to better estimates at the end of the cropping season with SAFY-CO₂.
Figure 9. Cumulated values of NEE for the 5 site-years: AUR2006, LAM2007, AUR2008, LAM2009 and AUR2010. The observations are displayed in black and the SAFYE-CO2 model outputs are in blue. The performances, in terms of relative mean square error (RRMSE), linear coefficient of correlation \(R^2\) and Nash criterion (Eff) are shown in the left bottom corner. The grey vertical bars indicate the period when the NEE fluxes are integrated over the cropping year for estimating the net ecosystem production (NEP, used for calculating the net ecosystem carbon budgets).
For AUR2010, SAFYE-CO2 underestimates the Reco from September to December, even if the Reco dynamics are better represented compared to SAFY-CO2 (not shown). This underestimation leads to lower performances at the end of the season with SAFYE-CO2. For AUR2006, the GPP event in September 2005 caused by re-growth was not simulated here but the SAFYE-CO2 version simulates better (and higher) Reco during this period than SAFY-CO2, causing higher divergences between observations and modeled values throughout the year. Also the water stress in June affects the GPP simulated by SAFYE-CO2 while this effect is not accounted for with SAFY-CO2.

In conclusion, the better estimation of Reco with SAFYE-CO2 highlights the problems encountered in simulating GPP correctly (e.g. re-growth event in 2005, low GPP at senescence in 2008, overall GPP underestimation in LAM2007) with both versions of the model. Therefore some strategies will be implemented to overcome this issue.

### 4.4. Components of the water budget

Using the original FAO-56 formalisms, the dynamics of simulated evapotranspiration (ETR) were compared to those measured at the Auradé and Lamasquère sites. As presented in section 2.2.3.2, the data of the site-years LAM2007 and AUR2008 were used for calibrating the parameters of the water budget module, and the other three site-years data sets (AUR2006, LAM2009, AUR2010) for validation (Figure 10). Table 7 summarizes the obtained performances, in terms of root mean square error (RMSE), correlation ($R^2$) and efficiency (Eff).

In general, we observe that the estimated ETR dynamics are in agreement with the measured ones, presenting a RMSE around 0.46 mm.d$^{-1}$, correlation coefficient ($R^2$) around 0.74 and efficiency (Eff) around 0.66. From the ETR dynamics, it is possible to identify the crop growth period, since they are similar to the GAI dynamics. We observe that in periods of bare soil: ETR is lower, since only the evaporation term contributes to the ETR estimation (no plant transpiration). Indeed, during the vegetation cycle, a gradual increase of the ETR (mainly because of plant transpiration) can be noted, which is directly related to the crop development (Béziat et al., 2013).

For LAM2007 (Figure 10, top), we observe that as for the GPP dynamics, the ETR are underestimated by SAFYE-CO2 during the crop growth maximal development phase. It is due to the early development of the wheat this year because of the particular climatic conditions, which led to very high true (destructive) GAI values at full crop development. This underestimation of higher values of ETR is clearly seen in the scatter plot (ETR$_{SIM}$ vs ETR$_{OBS}$, on the right), and is also confirmed by the regression slope of 0.74. In August, we can note a divergence between the model and the observations (enclosed in red), as the simulated ETR abruptly increase and the observations remain low. This increase in the simulated ETR corresponds to an increase in the reference evapotranspiration (ET0), i.e. a strong increase of the climatic evaporative demand. It means that the model responded more intensively to ET$_0$ than the measurements. During this period, the superficial SWC was overestimated by the model (not shown) which led to overestimated simulated...
evaporation. This divergence between the model and the measurements highlight the fact that the reference ET0 is overestimated by the original FAO-56 method.

For AUR2008 (Figure 10, 2nd), the simulated and observed ETR dynamics are quite well correlated ($R^2=0.78$) and present a low mean divergence (RMSE=0.42 mm.day$^{-1}$). A very slight overestimation can be noted around May (affecting the regression slope of 1.03), but it is not significant. LAM2007 and AUR2008 are the two data sets that were used for the calibration of the SAFYE-CO2 water balance module parameters. As expected, the established set of optimized parameters yields to good results for both years.

The data sets of 2006, 2009 and 2010 constitute the ‘validation’ data set. For AUR2006 (Figure 10, 3rd), we observe an overall agreement between simulated and measured dynamics of ETR. However, as for LAM2007, the ETR estimates are underestimated during the period of maximal development (from April until end of May). This is explained by low transpiration estimates at high GAI, which are related to the Kcb parameters. The results suggests that the value found for the Kcb$_{\text{max}}$ parameter through the calibration process (Kcb$_{\text{max}} =0.98$) is a bit low for the AUR2006 site. Two other particular divergences can be noted (enclosed in red): one in November (just after sowing), that corresponds to a strong rain event and probably overestimated ET0 estimated with the original FAO-56 method; the second occurs in October, when the observed ETR are stronger than the simulated by SAFYE-CO2. This divergence is probably caused by the crop re-growth development this year. Still, a good correlation coefficient ($R^2=0.75$) and a low root mean square error (RMSE= 0.47 mm.day$^{-1}$) are found.

For LAM2009 (Figure 10, 4th), an overall good agreement is obtained between observations and model estimates. A slightly underestimation tendency is shown by the analysis of the scatter plot (on the right), however, contrarily to the LAM2007 and AUR2006 years, the underestimation is not particularly concentrated during the periods of high plant development, but scattered during the cycle. A short peak in the simulations was observed in August that year, that could be caused by an overestimation of the ET0 by the FAO-56 method.

Finally, for AUR2010 (Figure 10, bottom), despite the overall good results ($R^2=0.75$ and RMSE= 0.50 mm.day$^{-1}$), an overestimation tendency by the model is observed (regression slope =1.1), which was not observed for the others years. It can be noted that in June, three peaks of ETR are simulated by the model and are not present on the measurements. These peaks correspond to peaks in the reference evapotranspiration (ET0). It means that once again the model was more sensitive to ET0 extreme values than the measurements.

From these results, we can conclude that in terms of ETR dynamics the calibration obtained using ETR data from two different sites and two contrasted climatic years (LAM2007 and AUR2008) yields to rather accurate ETR estimates but that the method for estimation ET0 during bare soil periods has to be improved. This is the reason why we corrected the reference ET0 following Soarès et al. (1988) as shown in Eq. [28]. The improvements of the evaporation estimates will be presented at the end of this document.
Table 6. Performances of the water balance components (ETR and SWC) dynamics estimated by the SAFYE-CO2 model using the original FAO-56 method for calculating ETo during bare soil periods for winter wheat over the experimental sites, from 2006 to 2010. For each year, the statistical indicators are calculated for the data collected from September until December of the following year.

<table>
<thead>
<tr>
<th></th>
<th>ETR</th>
<th>SWC-1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMSE*</td>
<td>R²</td>
</tr>
<tr>
<td>LAM2007</td>
<td>0.52</td>
<td>0.73</td>
</tr>
<tr>
<td>AUR2008</td>
<td>0.42</td>
<td>0.78</td>
</tr>
<tr>
<td>AUR2006</td>
<td>0.47</td>
<td>0.75</td>
</tr>
<tr>
<td>LAM2009</td>
<td>0.46</td>
<td>0.71</td>
</tr>
<tr>
<td>AUR2010</td>
<td>0.50</td>
<td>0.75</td>
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</table>

* RMSE in mm d⁻¹; ° RMSE in m³ m⁻³.

In order to calculate the cumulated evapotranspiration, we integrated the daily ETR over an agricultural year (from 1st October to 30th September). Figure 11 shows the comparison between the measurements and the SAFYE-CO2 estimates. For the five investigated years, we note that the simulated cumulative sum of ETR matches well with the observations during the crop season, especially for LAM2007, LAM2009 and AUR2010. Besides, for LAM2009 and AUR2010 (and a bit for AUR2008) it can be noted that at the beginning of the senescence phase (approximately early June), the model estimates diverge from the observations. It is due to an overestimation of the ETR by the model at the end of the season (overestimation of the ETo with the original FAO-56 method). This suggests that the model might not be optimally parameterized for periods of high evaporative climatic demand (mainly in summer) during bare soil periods. Still, for all the years an overall good agreement between model and measurements is obtained at the end of the season (with relative differences ranging from 3.9% to 16%).

Finally, evaluation of the cumulated ETR in terms of absolute values shows that 2007 was the climatic year that presented the higher water demand by the wheat crops (without considering the wheat varieties), because of its particularly warm autumn and winter seasons that led to strong GAI values and long vegetative period. Besides, we observe that there is not a particular site-dependent under or over-estimation trend. For AUR2006 and LAM2007 the model overestimates the total cumulated ETR, while for the others years (AUR2008, LAM2009 and AUR2010) the model provides underestimated ETR. When evaluating the model in terms of cumulated ETR inter-annual dynamics (see the bar plot, Figure 11 bottom right), without considering the absolute values, but their increase/decrease trends, we observe that for Auradé, from 2006 to 2008, according to the measurements the ETR decreases significantly (from 497 to 374 mm year⁻¹) while for the model, ETR remain practically constant for both years (=420mm.year⁻¹). It is due to the ETR underestimation during crop development in 2006. Comparing AUR2008 to AUR2010, the simulated trend is in agreement with the observations. For Lamasquère, from 2007 to 2009, both model and observations show a decrease in the total cumulated ETR.
Figure 10. Evolution of the ETR dynamics over winter wheat crop seasons for the calibration site-years (LAM2007 and AUR2008), followed by the validation site-years (AUR2006, LAM2009 and AUR2010). Observed ETR are represented in black and simulated ETR in blue. On the right, the scatter plots relating observed vs. simulated ETR and associated statistics (regression, RMSE, $R^2$ and efficiency Eff) are displayed.
The dynamics of simulated soil water content of the superficial (H1), root (H2) and deep (H3) layers were compared with those measured at the Auradé and Lamasquère sites (only results for 2006 are shown in Figure 12). The performances, in terms of root mean square error (RMSE), correlation ($R^2$) and efficiency (Eff) are summarized in Table 7. However, given the high spatial variability of the soil surfaces and relatively limited spatial representativeness of the in-situ measurements of soil humidity, the analysis here will be more qualitative than quantitative.

The soil superficial humidity (presented in the first line of Figure 12) is globally well reproduced by the model in terms of dynamics, however a bias on the absolute values is observed for all years. The models estimates are overestimated in comparison to the measurements, especially in 2007. The observed bias might be related to a poor initialization of the water content (for the three soil layers), conditioning the water balance results. We can also observe that both model and measurements respond instantly to precipitation events.

The root layer soil moisture dynamics are exhibited only during the crop growth, given that this layer is not simulated by the models during bare soil periods. Contrary to the top-layer, for the root layer the simulated moisture dynamics are smoother than the measurements. In general, as for the superficial layer, the SWC content is overestimated by the model. A possible reason for this fact is that transpiration does not take enough water from the root layer, inducing underestimated evapotranspiration for some years.

The simulated deep soil humidity remained practically constant over the whole year for LAM2007 and AUR2008. For AUR2006, a decrease in the deep soil moisture can be noted around May for both measurements and model estimates. It caused a water stress during this period, so the deep water reservoirs were required for maintaining the plant transpiration. A good agreement was observed between the model and the observations for LAM2009 and for AUR2010. Those years, the dynamic is well reproduced by the model, even if the SWC decrease between May and October is simulated with a lower intensity. In general, since this layer is driven exclusively by diffusive fluxes, it might be necessary to review the diffusion-related parameters, for better deep soil humidity estimates.
Figure 11. Evapotranspiration (ETR) during the agricultural year, for AUR2006, LAM2007, AUR2008, LAM2009 and AUR2010. Measured cumulated ETR are represented in black and simulated in blue. The cumulated ETR reached at the end of the season are indicated with the same representative colors and the difference between the measured and simulated values (in %) is displayed in grey. The calculated statistical indicators (RRMSE, \( R^2 \) and efficiency Eff) are displayed on the left top corner. On the right bottom corner the interannual dynamics of the total crop season cumulated ETR (observed and simulated) is shown for the Auradé (AUR2006, AUR2008, AUR2010) and Lamasquère (LAM2007, LAM2009) sites.
Figure 12. Comparison between the measured and simulated soil moistures for the Auradé site, 2006. The three soil layers are represented: H1, the superficial soil, H2, the root soil layer, and H3, the deep layer. The precipitation measurements are also indicated, and correspond to the right y-axis. The performances in terms of root mean square error (RMSE, m$^3$.m$^{-3}$) and correlation ($R^2$) are displayed in the top left corner.

4.5. Modification of the FAO-56 method for bare soil evaporation estimates

As pointed out in the previous section, it appeared that the simulated evaporation was overestimated during the bare soil periods with the original FAO-56 method. This is because evaporation is calculated as a function of the evaporative demand (ET0) in reference to a 12 cm high grassland. As a consequence, the slope ($\alpha$) of the linear relationship between $E$/ET0 and the superficial SWC was decreasing with increasing ET0 (Figure 13).
Soarès et al. (1988) had also identified this problem. Therefore we proceeded to a linear correction of the ETo. (see Eq. [28]) in order to obtain better estimates of the bare soil evaporation. Figure 13 shows that the relationship is very similar for the Auradé and Lamasquère sites. As a conclusion we used a generic parametrisation in [Eq. 28] (see the pink curve in Figure 13).

![Figure 13. This figure shows the remaining dependency to ETo of the slope (α) of the relationship between the evaporation normalized by ETo and the superficial SWC.](image)

Applying Eq. 28 during bare soil periods allowed us to improve our estimates of the cumulated evaporation compared to previous studies (Veloso 2014; Battude et al. 2017) considering the field measurements as the reference (Figure 14).

![Figure 14. Cumulative evaporation during the bare soil phases in Auradé (left) and Lamasquère (right) between 2006 and 2011 with the formulations of Battude et al. (2015), Veloso (2014) and with the modified FAO-56 version. The X axis represents the cumulative number of days with bare soil.](image)
4.6. Regional estimates

In this section, we present the results of the SAFYE SAFYE-CO2 model for the winter plots present in our study area (limited by the extent of Formosat-2 images). The model was run for the years 2006, 2007, 2010 and 2011. Figure 15 presents a general view of the area of study displaying the maximum GAI observed for the wheat fields of the investigated years all superposed, in order to have an idea of the broad scene. It shows that there is no clear regional pattern concerning maximum LAI distribution. Some of the output variables were selected in order to analyse the SAFYE-CO2 performances at regional scale. They are: maximum seasonal LAI, final aboveground biomass production, yield, the cumulated net CO2 fluxes at the end of the cropping year (i.e. NEP, from October to the end of September of the following civil year), the net ecosystem carbon budget (NECB) and the total ETR cumulated during the same period as NEE. For each year, the amount of available plots over the studied area varies: 373 for 2006, 369 for 2007, 512 for 2010 and 342 for 2011.

![General view of the study area, showing the winter wheat fields cultivated in 2006, 2007, 2010 and 2011 (superposed). The colors are illustrative and represent the maximum LAI, ranging from 0 up to 4 m².m⁻². The black rectangle shows the region that was selected for a closer look at SAFYE-CO2 estimates for the winter wheat.](image)

Figure 16 shows that the maximum seasonal LAI (LAImax) estimated by SAFYE-CO2 is similar for the four investigated years and ranges from 2.44 m².m⁻² (in 2006) up to 2.80 m².m⁻² (in 2010). However for the minimal estimated LAImax, we observe that in 2007 it was equal to 1.49 m².m⁻², while for the other years lower values were found. It is probably due to the warm winter temperatures of the 2007 crop season, that induced an early and strong development of the vegetation (as discussed
before for Lamasquère 2007). Still, in general, the inter-annual variability of LAImax are not pronounced, even if those years had contrasted climatic conditions. For example, 2006 and 2011 were rather dry years for winter crops, and plants were subjected to water stress, while 2007 and 2010 were rather wet years.

Figure 16. From the top to the bottom, maps of maximum seasonal LAI, final biomass, yield, net ecosystem production at the end of the season (NEP), net ecosystem carbon budget (NECB) and cumulated evapotranspiration (ETR) estimated by the SAFYE-CO2 model for a number of plots within the study area over the 2006, 2007, 2010 and 2011 years. The color scales are displayed on the right of each serie.
On the opposite, our destructive measurements (not shown) showed high variability in GAI. This lack of inter-annual variability in the modelled maximum GAI may be caused by saturation effects in satellite-derived GAI estimates, which does not allow the model to reproduce the real GAI temporal and spatial variability in our area of study. However, it can be noted that in 2006 the GAI values are slightly inferior compared to the other years. Besides, we observe that the fields of the 2011 year seem to have more spatial variability than for the other years. This might be due to the exceptional dry character of the 2011 winter wheat season, so the soil types (and soil reservoirs) play a determinant role over the crop development, that may lead to higher inter-plots variability.

For the final biomass production estimates, the values ranged from a minimum of 458 g m\(^{-2}\) (2011) to a maximum of 1518 g m\(^{-2}\) (2007). The mean biomass values varied from 996 g m\(^{-2}\) for 2011 to 1230 g m\(^{-2}\) for 2010. The standard deviation between biomass estimates from plots of the same year is not very strong (about 50 g m\(^{-2}\)). However, from these min/max ranges the effect of the climatic conditions over the biomass estimates can be seen. According to the model, the lower biomass estimates were obtained for the dryer years (2006 and 2011), while for the wet years (2007 and 2010) the estimates are slightly superior. By the analysis of the maps, it can be noted that the strongest values of biomass estimates are related to those of LAI estimates; and the same for the low values: plots having low biomass, in general produce lower LAI. In 2011, a particular field captured out attention because of its low biomass estimate. This plot barely reaches a LAImax of 1.5 m\(^2\).m\(^{-2}\) (which is low for winter wheat), inducing a final biomass estimate around 700 g m\(^{-2}\). Furthermore, since the yield here is estimated from the final biomass by a constant harvest index, the yield maps have basically the same characteristics as the biomass ones.

For the maximum LAI, biomass and yield outputs the model provides realistic estimates over the whole study area. For instance, concerning yield, regional statistics in Haute-Garonne give average values ranging from 4.2 to 5.5 t.ha\(^{-1}\) between 2006 and 2010, which is in god agreement with the mean values provided by the model estimates.

Concerning the net CO\(_2\) fluxes estimates, the cumulated NEE varies from -502 gC m\(^{-2}\).y\(^{-1}\) (in 2010, strong net CO\(_2\) assimilation) up to 186 gC m\(^{-2}\).y\(^{-1}\) (2011, carbon release). According to the investigated year, the mean cumulated NEE may be quite different, e.g. NEP=-219 gC m\(^{-2}\).y\(^{-1}\) for 2011 and about -312 gC m\(^{-2}\).y\(^{-1}\) for 2006. Still, the mean NEP is negative for the four years, representing a sink for atmospheric CO\(_2\) by the crops. Even so, some plots presented positive NEP, representing a CO\(_2\) source, but these plots are few. These results are coherent with those observed by Béziat et al., (2009) for the crop rotations of the Auradé and Lamasquère sites. In this study, all NEPs were negative, corresponding to CO\(_2\) sinks, which is also consistent with other studies on winter wheat and triticale (e.g. Ceschia et al. 2010).

In Ceschia et al., (2010), on average, winter crops had rather similar NEPs, with -292 ± 170 gC m\(^{-2}\).y\(^{-1}\) (for n=13 observations) and -358 gC m\(^{-2}\).y\(^{-1}\) (n = 2), for common winter wheat and durum wheat, respectively, located over different sites in Europe. When considering all the wheat varieties together, the mean NEP and associated standard deviation was -326 ± 132 gC m\(^{-2}\).y\(^{-1}\). The range of values of the NEP simulated by SAFYE-CO2 is therefore included within the values reported by Ceschia et al. (2010).

In terms of carbon budgets, the average NECB calculated for each year for our study area indicates that, except for 2007, the wheat ecosystems acted as CO2 sinks, presenting negative NECB. We obtained NECBs of -101 ± 25, -78 ± 24 and -19 ± 38 gC m\(^{-2}\).y\(^{-1}\) for 2006, 2010 and 2011, respectively.
For 2007, NECB was $13 \pm 38 \text{ m}^2\text{.y}^{-1}$, being close to neutrality. Furthermore, when evaluating the minimal and maximal NECB values found for each year, we observe that some plots can have very different NECB (spatial variability) even if the climatic conditions on these plots were essentially the same. The largest interval of variation was found for 2011, for which plots NECB varied between $-220.67$ and $274.96 \text{ m}^2\text{.y}^{-1}$. For the SAFYE-CO2 results presented in this section, we considered the hypothesis that only grain was exported and straw was left on site, what is true for the majority of fields within our zone of study. However, it is worth noting that in 2011 the straw was exported on many plots of our study area in order to compensate the lack of forage production at the national level. Accounting for straw removal at some plots would have increased the spatial variability in NECB estimates in 2011.

To simulate the impact of this change in the straw management over the carbon budget, we recalculated the NECB for the 2011 plots by considering that the $C_{\text{exp}}$ term was composed of grains plus a fraction of the straw (not shown). For the first case, when only the grains are exported, the average NECB for 2011 was of $-18.6 \pm 38.2 \text{ gC m}^2\text{.y}^{-1}$, representing a small CO2 sink. For the second hypothesis (grain and straw exported), the mean NECB raise to $659.9 \pm 50.7 \text{ gC m}^2\text{.y}^{-1}$, representing a strong CO2 source, showing the significant impact that this management practice may have on carbon budgets.

On average, the NECB for the different crop species examined by Ceschia et al., (2010) was $138 \pm 239 \text{ gC gC m}^2\text{.y}^{-1}$, corresponding to a carbon source, but the variability in the observations (caused by differences in straw, organic fertilization management and climatic gradients) surrounding this estimate was larger than the source itself. Considering a mean soil organic C content of $5300 \text{ gC m}^2$ (53 t of organic C ha$^{-1}$ to a depth of 30 cm) in European agricultural soils, the mean NECB would correspond to an annual loss of $2.6 \pm 4.5\%$ of the soil organic C content. Of course, this value should be considered with caution because the crop species, soil conditions and management practices in the Ceschia’s study are probably not fully representative of all croplands found in Europe. For our study, focused on the winter wheat crop, the average estimated NECB was $-46 \pm 53 \text{ gC m}^2\text{.y}^{-1}$, corresponding to a carbon sink, but close to equilibrium and the variability of this term was higher than the estimate itself. In terms of soil organic C content, our results on winter wheat would correspond to an annual gain of $0.87 \pm 1\%$. This variability was caused mainly by differences in climatic conditions, soil characteristics and some of the management practices (as dates of sowing and harvest). The management regimes concerning organic fertilization and straw removal were assumed to be similar for all the investigated plots, since this information is not available at the regional scale, and thus do not represent a source of variability between plots and years.

### 5. Performance of the model for summer crops

In order to present the performance of the model to simulate summer, we choose to show our results for sunflower and maize which are among the dominant crops in our area of study together with winter wheat. Unfortunately, we only had two years of flux measurement for sunflower at the Auradé site.
In this section we’ll present briefly the results relative to the plant module (i.e. results concerning the LAI, the biomass, the CO₂ fluxes and the C budget) as our simulation results for summer crops aim at showing the performances of the specific plant parametrisation (see the Supplemental section). Also, at this stage, no change in the soil module was performed for the summer crops compared to winter wheat.

5.1. LAI and Biomass

For the two sunflower cropping years, the model reproduced very well the LAI and the aboveground biomass dynamics (see Figure 17 and 18).

![Figure 17. On the left, LAI seasonal dynamic simulated (blue), estimated by remote sensing (using SPOT and Formosat 2 images, respectively in green and in red) and measured on the field (white dots) in 2007 at Auradé. On the right, simulated biomass (blue curve) and field observations (dots) in 2007 at Auradé.](image)
Figure 18. On the top, aboveground biomass (DAM) seasonal dynamic measured in the field (red dots) and simulated (best simulation in blue, median of the 10 best simulations in black and 2nd to 10th best simulations in green) in 2016 at Auradé. On the bottom, relative error of the simulated biomass.

Figures 18 shows that the median and the best DAM estimates are quite close and both Figure 17 and 18 show that the best estimate is within the range of uncertainty of the field measurements.

5.2. Evaluation of the CO₂ fluxes

The dynamics of the measured and simulated gross primary production (GPP), ecosystem respiration (Reco), net CO₂ ecosystem exchange (NEE) for the two years of measurements on sunflower at Auradé and for the maize in 2010 at Lamasquère are presented in Figures 19, 20 and 21.

For all years, the model shows very good performances in simulating the components of the NEE and the dynamics of the fluxes are well reproduced. Note however that before sunflower development in 2007 (Fig. 19), field measurements indicate significant GPP fluxes and some positive NEE fluxes indicating that significant photosynthesis is occurring at the site. However, the soil was absolutely bare during this period (no presence of vegetation) which indicates an artefact in the measurements.

When analysing the cumulated NEE of maize for the Lamasquère site in 2008 (Fig. 22), the results show very good agreement with the observations with R², RMSE and bias of respectively, 3.82, 0.97 and 14.73.
Figure 19. Seasonal evolution of the CO₂ fluxes (GPP, Reco, NEE respectively) for the Auradé site in 2007. Observed fluxes are represented in red and simulated fluxes in blue. On the right the scatter plots relating observed vs. simulated variables and associated statistics (regression, RMSE and $R^2$) are displayed.

Figure 20. Seasonal evolution of the CO₂ fluxes (GPP, Reco, NEE respectively) for the Auradé site in 2016. Observed fluxes are represented in red and simulated fluxes in blue. On the right the scatter plots relating observed vs. simulated variables and associated statistics (regression, RMSE and $R^2$) are displayed.
Figure 21. Seasonal evolution of the CO₂ fluxes (GPP, Reco, NEE respectively) for the maize at the Lamasquère site in 2010. Observed fluxes are represented in red and simulated fluxes in blue. On the right the scatter plots relating observed vs. simulated variables and associated statistics (regression, RMSE and $R^2$) are displayed.

Figure 22. Cumulated values of NEE for maize at the Lamasquère site in 2008. The observations are displayed in red and the SAFYE-CO₂ model estimates are in blue. The performances, in terms of relative mean square error (RRMSE), linear coefficient of correlation ($R^2$) and final bias are shown in the left bottom corner.
5.3. Carbon budget

In this section we present the performances of the model to estimate the components of the carbon budgets of the two sunflower years at Auradé (i.e. in 2007 and in 2016). As shown in Figure 23, the model tends to underestimate the export of carbon at harvest even if the biomass were correctly estimates (see Fig. 17 and 18). This underestimation of the $C_{\text{exp}}$ term could be caused by an understimation of the harvest index (HI) for sunflower. Literature analysis may provide more accurate estimates of the HI.

In 2016 the model estimated accurately the net annual CO$_2$ flux. However, in 2007 a strong difference is observed between the in-situ measurements and the model estimates. This difference is cause by an error in the flux measurements, as mentioned in the section above. This error results in strong divergences in the C budget calculation for 2007. At the opposite, the observed and simulated C budget estimates in 2016 are close and the divergence comes from the underestimation of the HI for sunflower.

Figure 23. Annual net ecosystem carbon budgets (NECB) and their components (NEP, Cinp, Cexp) derived from the in-situ data and modeled (full and dashed bars respectively) for the 2007 (left) and 2016 (right) sunflower years at Auradé.
6. Conclusion

We demonstrated here the potential of high resolution remote-sensing data assimilation in a semi-physical crop model (SAFY-CO2) to successfully provide estimates of some of the main agronomical variables (yield, biomass) as well as the components of the cropland carbon and water budgets for several crop species. While this modeling approach is promising because it requires few input parameters and few data concerning management for estimating crop production, evapotranspiration and net CO2 fluxes, it must be considered as a first step for filling the gap that exists to obtain an accurate and spatially explicit representation of the main components of the cropland carbon and water budgets at the regional scale. Indeed, the main limitation of this approach is that, in areas concerned by animal farming, the calculation of the carbon budget requires data on i) organic amendments and ii) the fraction of straw exported at harvest, which cannot be retrieved by remote sensing at this stage. Also, at this stage, irrigation must be prescribed to the model in order to calculate accurate water budgets even if Battude et al. (2017) have tested an irrigation module that could be coupled to SAFYE-CO2.

Till now, one of the main limitation concerned the availability of satellite observations since our approach is data driven... However, thanks to the recent HTRS satellite missions (Sentinel 1 & 2), this type of approach could be generalized, more accurate and more robust. Indeed, the synthetic aperture radar satellites (e.g. Sentinel-1) will enable to overcome cloudy conditions (Veloso et al., 2017). Our results also show that the performances of the model for estimating the net CO2 fluxes and thus the C budgets are significantly improved by considering the development of weeds and crop re-growth after harvest. These events, or the presence of cover crops in the crop rotation, are rarely or never accounted for in regional or global modeling of CO2 fluxes, although our results show that they significantly impact the cropland carbon budgets.

In the perspective of future global scale applications, this approach could be strengthened (validated for a wider range of climates and management regimes) and extended to other crops by using data from international flux networks (e.g. ICOS and FLUXNET) and from recent HTRS satellite missions.
Reference documents


## Supplemental information

**Table 7. List of the SAFYE-CO2 crop model parameters, notation, units, values or range and the methods of calibration for the sunflower crop.**

<table>
<thead>
<tr>
<th>Description</th>
<th>Notation</th>
<th>Unit</th>
<th>Value/Range</th>
<th>Method</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climatic efficiency</td>
<td>$\varepsilon_c$</td>
<td>-</td>
<td>0.48</td>
<td>Literature</td>
<td>Varlet-Grancher (1982)</td>
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Table 8. List of the SAFYE-CO2 crop model parameters, notation, units, values or range and the methods of calibration for the maize crop.

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<th>Description</th>
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