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Estimation of Crop Production and CO_2 Fluxes Using Remote Sensing: Application to a Winter Wheat/Sunflower Rotation †

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Abstract: To meet the incoming growth of the world's food needs, and the demands of climate change, the agricultural sector will be forced to adapt its practices. To do so, the contribution of agricultural fields to greenhouse gas emissions, as well as the impact—on soil, climate and productions—of certain agricultural practices have to be known. In this study, the SAFY-CO_2 crop model is driven by remote sensing products in order to estimate CO_2 fluxes on the main crop rotation observed in the study area, i.e., winter wheat followed by sunflower. Different modeling scenarios are tested, particularly for intercropping periods, the approach being validated locally, thanks to eddy covariance flux measurements, and then applied regionally. Results showed that the model was able to reproduce crop production with high accuracy (rRMSE of 21% and 24% for winter wheat and sunflower yield, respectively) as well as daily net CO_2 flux (RMSE of 1.29 and 0.97 $gC.m^{-2}.d^{-1}$ for winter wheat and sunflower respectively). Moreover, the tested modeling scenarios highlight the importance of taking the regrowth events into account for assessing accurate carbon budgets. In a perspective of large-scale application, the model was upscaled over more than 100 plots, allowing discussion of the effect of regrowth on carbon uptake.

Keywords: crop modeling; remote sensing; CO_2 fluxes; croplands; regrowth

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1. Introduction

Agriculture is one of the main contributors to global greenhouse gas (GHG) emissions, with almost 12% of the total emissions in 2017 (source: FAO). Because of the heterogeneous character of the croplands, it is challenging to accurately assess agronomic indicators such as production or CO_2 fluxes at plot scale over large areas. The general process-based models (Ecosys [1], Isba-Ags [2], ORCHIDEE [3], etc.) are designed to simulate carbon cycle in different ecosystems, but they have difficulties in representing agricultural ecosystems because of their various climate and soil conditions. On the other hand, agronomic models (STICS [4], Cropsyst [5], CERES [6], etc.) are suitable to assess accurate CO_2 fluxes over croplands, but they need information on management practices and cultivars that make them ill-adapted for upscaling. In this context, the simple crop model, SAFY-CO_2, was developed and combined with remote sensing products (taking advantage of the regular observations of vegetation states) to estimate the vegetation development, production, and CO_2 fluxes over croplands.

The long-term objective of this research is to evaluate the impact (on production, carbon, and water fluxes) of certain agricultural practices and rotations at plot scale over wide areas. The most cultivated crops must therefore be calibrated first in order to simulate crop rotations and different scenarios during the off-season (bare soil, cover crops, mulching, etc.). Winter wheat and sunflower are the two main crops cultivated in southwest France and have already been validated. The authors of [7] validated SAFY-CO_2 for winter wheat on biomass, yield, and CO_2 fluxes and notably estimated the daily net CO_2 flux (NEE—net ecosystem exchange) with good accuracy (RMSE = 1.29 gC.m^{-2}.d^{-1}). More recently, [8] validated the model for sunflower and showed that the model also reproduced the NEE with high accuracy (RMSE = 0.97 gC.m^{-2}.d^{-1}). Estimating NEE properly is a prerequisite for assessing a carbon budget.

The objective of this study is to estimate crop production, and more particularly CO_2 fluxes during a crop rotation, with particular attention to the intercrop period. The proposed approach is based on the agro-meteorological SAFY-CO_2 model, driven by optical satellite-derived products, considering two modeling scenarios. The different variables needed for the study, as well as the main steps taken into account in the methodology are described in Section 2. The results are analyzed and discussed (Sections 3 and 4), focusing first on the validation of the estimated fluxes at the plot scale, and then on estimates performed on a 14 by 13 km^2 area, or more than 100 plots.

2. Experiments

2.1. Study Area

The study area was located in an agricultural region governed by a temperate climate (Figure 1). The seasonality of weather conditions allowed the cultivation of the main crops encountered in France, distinguishing "winter crops" (mainly represented by wheat) and "summer crops" (mainly represented by sunflower). The relief was characterized by hilly landscapes that result in heterogeneous development of crops. Since 2005, continuous measurements of meteorological variables, CO_2, and water fluxes were performed on a plot near Auradé (an instrumental location that is part of the ICOS network: https://www.icos-cp.eu/, accessed on 2 April 2021; hereafter called FR-Aur), together with a regular survey of crop biomass and agricultural practices. In this study, the analysis focused first on winter wheat grown in the 2005–2006 season, followed by sunflower grown in the 2006–2007 season, considering the FR-Aur plot. Then the same rotation was studied on 111 fields and over different crop years (2013–2014 and 2014–2015).

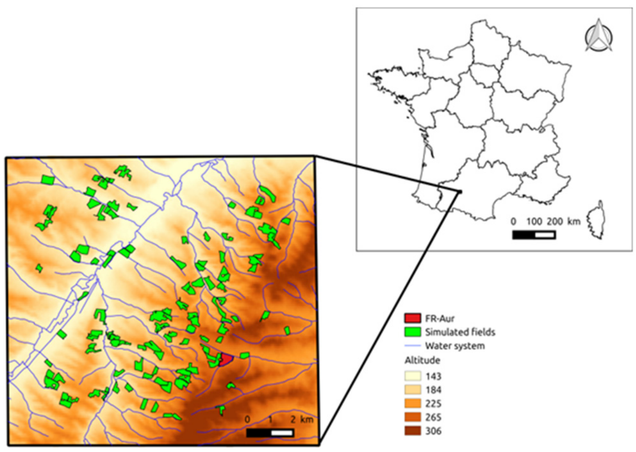

Figure 1. Location of the study area in France. The altitude (m) is displayed in the background.

2.2. Meteorological, Fluxes, and Satellite Data

The daily meteorological inputs of the model (that is, air temperature and global incoming radiation) were either measured at FR-Aur (for local simulations) or provided by SAFRAN reanalysis [9] for simulation at a larger scale. The SAFRAN meteorological data were provided all over France at a daily time-step and at a spatial resolution of 8 × 8 km^2.

The components needed to obtain CO_2 fluxes were measured using the eddy covariance method. Turbulent fluxes were then derived from EdiRe software, and post-processed (filtering, quality controls, and gap filling) in accordance with the CarboEurope-IP recommendations. Finally, the gross primary productivity (GPP) and ecosystem respiration (R_{ECO}) were derived from the partitioning of the NEE values of CO_2. See [7] for more details on the procedure.

The timeline of the optical satellite images acquired during the four considered crop years is presented in Figure 2. Regular high-spatial-resolution images were provided by Formosat-2 (43, 14, and 17 images for the years 2006, 2007, and 2014 respectively), SPOT-2/4 (4, 7, and 27 images for the years 2006, 2007, and 2015) and LANDSAT-8 (16 and 15 images for the year 2015 and 2016). Finally the Green Area Index (GAI) were derived from surface reflectances by the mean of the biophysical variables neural network tool [10] and averaged at the plot scale.

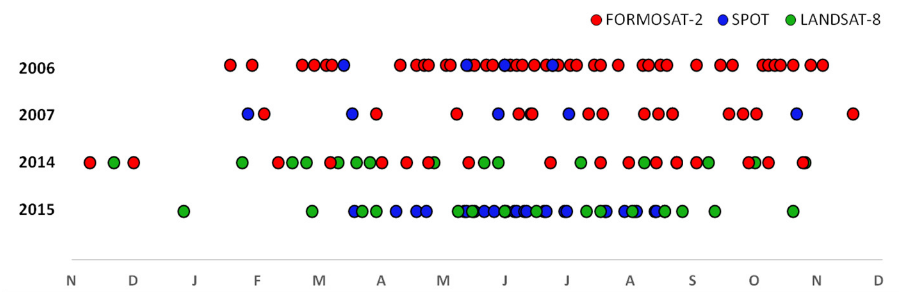

Figure 2. Timeline of satellite images used in this study.

2.3. Methods

The daily time-step SAFY-CO_2 model simulates the temporal evolutions of vegetation variables (GAI, biomass, and yield) and CO_2 fluxes using climate input variables (air temperature and global incoming radiation). The agronomic formalisms have already been presented and detailed in previous studies ([7,11,12]), so the equations of the model will not be presented here. The parameters of the model are either fixed, extracted from literature or measurements; or variable and constrained by boundaries. They are crop-specific and fully detailed in [7,8] for winter wheat and sunflower, respectively. On each simulated field and each year independently, the values of the eight calibrated parameters are determined by minimizing the quadratic difference between the simulated and satellite-derived GAI (process detailed in [7]), through a constrained version of the simplex method [13]. This step allows the model to reproduce all types of developments observed (by satellites) on the considered fields.

In the present study, the model is validated at a local scale over a winter wheat/sunflower rotation covering two crop years (2005–2006 and 2006–2007) using CO_2 flux measurements. Then the same rotation is simulated at a larger scale on 111 fields and over two different crop years (2013–2014 and 2014–2015). In the two modeling exercises (i.e., local and regional scale), two scenarios were considered, i.e., with and without simulation of regrowth events.

3. Results

3.1. Local Validation at FR-Aur

Figure 3 presents the temporal evolutions of the net CO_2 flux (NEE) and its components (the GPP and the R_{ECO}) and Table 1 summarizes the performances of the model in estimating these three variables for the different periods of simulation (characterized by different colors in Figure 3). Since there is no GPP during the bare-soil period, GPP statistics are calculated over the vegetation period (from sowing to harvest and during off-season when regrowth is simulated).

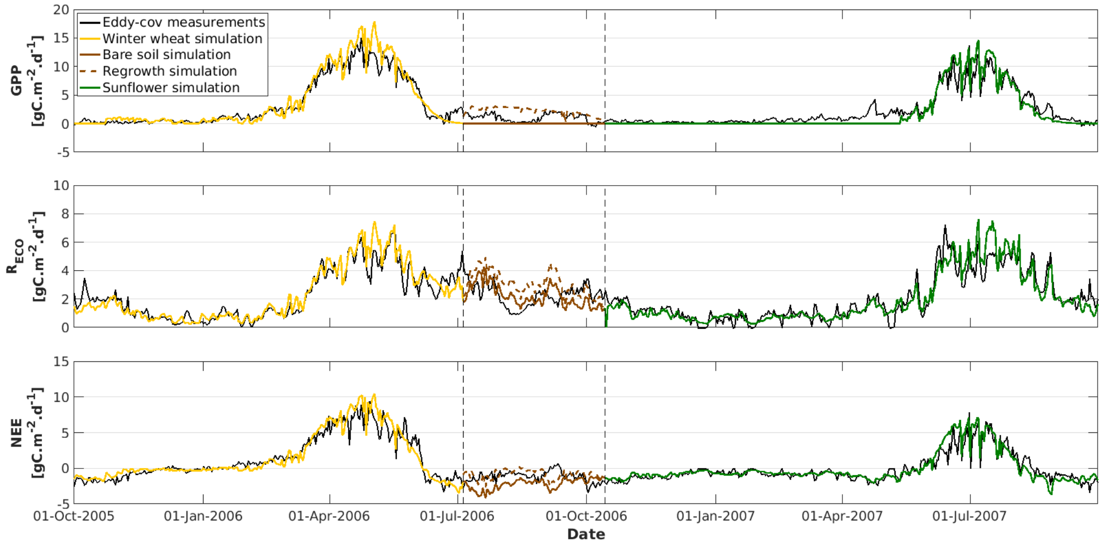

Figure 3. Temporal evolutions of the gross primary productivity (GPP), the ecosystem respiration (RECO), and the net ecosystem exchange (NEE). Winter wheat, bare soil, regrowth, and sunflower periods are displayed in yellow, brown, dashed brown, and green respectively.

Table 1. Summary of model's performances in estimating GPP, RECO, and NEE for different time periods corresponding to different surface occupations.

		R^2	RMSE [gC.m^{-2}.d^{-1}]	Mean Bias [gC.m^{-2}.d^{-1}]
GPP	2-year period	0.93	1.49	0.28
	Winter wheat season	0.94	1.48	0.38
	Regrowth period	0.03	1.46	1.15
	Sunflower season	0.92	1.50	0.09
RECO	2-year period	0.83	0.70	0.00
	Winter wheat season	0.88	0.66	0.07
	Bare soil period	0.05	0.93	−0.08
	Regrowth period	0.01	1.30	0.75
	Sunflower season	0.86	0.66	−0.04
NEE	2-year period	0.86	1.06	−0.06
	Winter wheat season	0.89	1.10	0.12
	Bare soil period	0.10	1.58	−1.02
	Regrowth period	0.02	1.11	0.31
	Sunflower season	0.86	0.80	0.08

The model was able to accurately reproduce the three temporal dynamics. Indeed, over the entire simulation period (i.e., two years) the model showed very good correlations with observations (R^2 of 0.93, 0.83, and 0.86 for GPP, RECO, and NEE, respectively) and low errors (RMSE of 1.49, 0.70, and 1.06 gC.m^{-2}.d^{-1} for GPP, RECO, and NEE, respectively). Regarding the off-season period (delimited by vertical dashed lines on Figure 3), no correlations were found for the three simulated variables. This period was characterized by very heterogeneous weed development on the field. Since the model is calibrated thanks to remote-sensed GAI averaged over the entire plot, this heterogeneity is 'smoothed' in the optimization process and thus in the model outputs. Conversely, CO_2 flux measurements are representative of a specific area, inside the plot, which change according to the wind. In these conditions, it would be a hard task to represent accurately the dynamic of the CO_2 fluxes. Nevertheless, taking regrowth events into account allows significant improvement of the CO_2 flux estimates. Indeed, over this period (corresponding to 102 days), the difference between simulated and measured NEE is 87% (104.1 gC.m^{-2}), while it is reduced to −27% (−31.4 gC.m^{-2}) when considering regrowth.

3.2. Model's Upscaling

The values of net ecosystem productivity (NEP, equal to the NEE integrated over a time period) estimated over 111 fields without consideration of regrowth are presented in Figure 4A. The NEP obtained from the most-observed crop rotation within the study area varies between −186.4 and 298.1 gC.m^{-2}.yr^{-1}. The majority of plots are therefore considered to be carbon sinks. Nevertheless, 23% of the plots cultivated with these two crops behave as sources. The average NEP value considering this scenario is −44.1 gC.m^{-2}.yr^{-1}, while that taking regrowth into account is close to −59.0 gC.m^{-2}.yr^{-1}. This slight difference between the two scenarios can be explained by the low number of plots with regrowth events. Indeed, among the considered plots, 24 presented regrowth events (identifiable through remote-sensed GAI dynamics). Figure 4B presents the difference of NEP between simulations without and with taking regrowth into account.

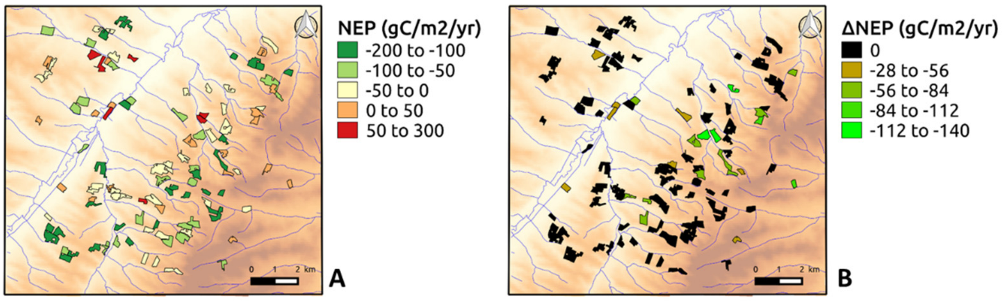

Figure 4. Spatial distribution of the net ecosystem productivity (NEP) simulated over 111 fields without taking regrowth events into account (**A**), and the differences in the scenario where regrowth events are considered (**B**).

Taking regrowth into account increases the carbon sink of the considered plot from −28.0 to −139.5 gC.m^{-2}.yr^{-1}. Considering only plots where regrowth was simulated, the average NEP varies from −16.1 gC.m^{-2}.yr^{-1} (bare soil simulated) to −85.2 gC.m^{-2}.yr^{-1} (regrowth simulated). Furthermore, among the 24 plots concerned by regrowth events, 12 behaved as a source of carbon without considering regrowth, while only 4 remained a source after regrowth simulation. Indeed, because the carbon assimilation period is longer when vegetation developed on a field during the off-season, the NEP is lower (more negative). This means that it increases the plot's carbon sink.

4. Discussion

In this study, the SAFY-CO_2 model has been adapted to simulate crop rotations. So far, only winter wheat and sunflower crops are calibrated, so only rotations between these two crops can be simulated. A generic parametrization has also been defined for regrowth events, allowing improvements in NEE, and thus the estimated NEP, which is crucial when trying to assess carbon budgets.

To the best of our knowledge, no crop model considers regrowth events to assess NEP and thus net ecosystem carbon budget (NECB). We demonstrated here that these events could have important impact on CO_2 fluxes that needs to be considered when simulating crop rotations. Indeed, the development of cover crops at large scale could have a strong mitigation impact via atmospheric carbon storage in soils and could be quantified with a tool such as SAFY-CO_2.

So far, we are not able to identify the nature of regrowth (i.e., weeds, cover crop, or spontaneous regrowth) so the same parametrization was used to simulate all regrowth events. In the near future and in order to improve regrowth simulations, the parametrization of the regrowth will have to be refined according to the nature of the regrowth, which could be retrieved by the use of radar products. Indeed, the radar could give information on the nature of the regrowth through the geometry of the cover.

5. Conclusions

In the proposed study, the SAFY-CO_2 model was applied to a winter wheat/sunflower rotation, offering satisfactory performances concerning the estimation of net CO_2 fluxes and its components. Over the two simulated crop years at FR-Aur, the model estimated the net CO_2 flux with high correlation (R^2 = 0.86) and low error (RMSE = 1.06 $gC.m^{-2}.d^{-1}$). The modeling scenarios highlighted the importance of taking the regrowth events into account for assessing accurate carbon budgets. On the plot equipped with a flux tower, the estimates taking regrowth (weeds in this case) into account allowed reduction of the error on the NEP from 87% to −27%. On a larger scale, regrowth events increased the carbon sequestration capacity observed during a two-year crop rotation, with values ranging from −28.0 to −139.5 $gC.m^{-2}.yr^{-1}$.

The approach proposed in this study constitutes a diagnostic tool, particularly promising in a context where intercrop periods tend to be vegetalized. With a view to carrying out assessments integrating a greater diversity of crops, future studies should focus on the parameterization of maize, rapeseed, or soybean, as well as on the characterization of intermediate crops.

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