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# ORCHIDEE-CROP (v0), a new process based Agro-Land Surface Model: model description and evaluation over Europe

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## Abstract

The responses of crop functioning to changing climate and atmospheric CO<sub>2</sub> concentration ([CO<sub>2</sub>]) could have large effects on food production, and impact carbon, water and energy fluxes, causing feedbacks to climate. To simulate the responses of temperate crops to changing climate and [CO<sub>2</sub>], accounting for the specific phenology of crops mediated by management practice, we present here the development of a process-oriented terrestrial biogeochemical model named ORCHIDEE-CROP (v0), which integrates a *generic* crop phenology and harvest module and a very simple parameterization of nitrogen fertilization, into the land surface model (LSM) ORCHIDEEv196, in order to simulate biophysical and biochemical interactions in croplands, as well as plant productivity and harvested yield. The model is applicable for a range of temperate crops, but it is tested here for maize and winter wheat, with the phenological parameterizations of two European varieties originating from the STICS agronomical model. We evaluate the ORCHIDEE-CROP (v0) model against eddy covariance and biometric measurements at 7 winter wheat and maize sites in Europe. The specific ecosystem variables used in the evaluation are CO<sub>2</sub> fluxes (NEE), latent heat and sensible heat fluxes. Additional measurements of leaf area index (LAI), aboveground biomass and yield are used as well. Evaluation results reveal that ORCHIDEE-CROP (v0) reproduces the observed timing of crop development stages and the amplitude of pertaining LAI changes in contrast to ORCHIDEEv196 in which by default crops have the same phenology than grass. A near-halving of the root mean square error of LAI from  $2.38 \pm 0.77$  to  $1.08 \pm 0.34 \text{ m}^2 \text{ m}^{-2}$  is obtained between ORCHIDEEv196 and ORCHIDEE-CROP (v0) across the 7 study sites. Improved crop phenology and carbon allocation lead to a general good match between modelled and observed aboveground biomass (with a normalized root mean squared error (NRMSE) of 11.0–54.2%), crop yield, as well as of the daily carbon and energy fluxes with NRMSE of  $\sim 9.0$ –20.1 and  $\sim 9.4$ –22.3% for NEE, and sensible and latent heat fluxes, respectively. The model data mistfit for energy fluxes are within uncertainties of the measurements, which them-

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selves show an incomplete energy balance closure within the range 80.6–86.3%. The remaining discrepancies between modelled and observed LAI and other variables at specific sites are partly attributable to unrealistic representation of management events. In addition, ORCHIDEE-CROP (v0) is shown to have the ability to capture the spatial gradients of carbon and energy-related variables, such as gross primary productivity, NEE, sensible heat fluxes and latent heat fluxes, across the sites in Europe, an important requirement for future spatially explicit simulations. Further improvement of the model with an explicit parameterization of nutrition dynamics and of management, is expected to improve its predictive ability to simulate croplands in an Earth System Model.

## 1 Introduction

Croplands cover ~ 12% of the land surface (Ramankutty and Foley, 1998), with temporal and spatial variations being subject to population increase, changes in diet, market prices and other socio-economic factors (IPCC, 2014; Ramankutty et al., 2002; Vuichard et al., 2008). The responses of croplands to climate change are expected to have significant, but uncertain, consequences for (1) global food production and (2) land surface water, carbon and energy fluxes, which affects food security as well as regional climate and water resources (Bonan, 2008, 2001; Loarie et al., 2011; Rosenzweig et al., 2014).

Along with understanding of crop physiology to improve production and yield quality, research has focused on investigating the climate impacts on crop functioning by combining historical observations with statistical models (Lobell and Field, 2007; Lobell et al., 2011; Rosenzweig and Parry, 1994) or by running crop models from site to global scales. Impact studies always pointed out to a significant contribution of climate on crop yield variability (Lobell and Field, 2007; Parry et al., 2005; Rosenzweig et al., 2013). However, discrepancies in the response to climate change between different crop mod-

els highlighted uncertainties related to model structure, parameterization, and external drivers (Asseng et al., 2013; Müller, 2011; Rosenzweig et al., 2013).

Besides, there is an increasing need of better understanding the environmental and climate consequences of changes in cropland area and in management practice, via modification of biophysical and biogeochemical land–atmosphere fluxes (Foley et al., 2011; Lobell et al., 2006; Osborne et al., 2009; Tubiello et al., 2007). Multiple lines of evidence show that changes of cropland plant properties can modify strongly enough the biophysical characteristics (albedo, roughness, turbulent fluxes) of the land surface to have an effect on local and regional climate (Davin et al., 2014; Foley et al., 2011; Georgescu et al., 2009; Loarie et al., 2011; Osborne et al., 2009).

Investigation of cropland-climate interactions led to model developments to improve Land Surface Models (LSMs) for including a more realistic representation of crop processes (Bondeau et al., 2007; Gervois et al., 2004; Kucharik, 2003), aiming to simulate the spatial distribution and variability of crop production as well as their water, energy, and carbon fluxes which affect climate. These efforts have improved the seasonal dynamics of modeled foliar and biomass developments (Bondeau et al., 2007; Gervois et al., 2004, 2008; Kucharik, 2003; Valade et al., 2014; Van den Hoof et al., 2011) and long-term soil carbon changes (Ciais et al., 2011). Despite progress, these “Agro-LSM” models have shown limitations such as (1) static or crop/region specific parameterizations (Berg et al., 2011; Kucharik, 2003); (2) idealized representation of different crop types and cultivation practice (Bondeau et al., 2007); (3) Incomplete coupling between crop growth parameterizations and LSM processes (de Noblet-Ducoudré et al., 2004; Gervois et al., 2004; Valade et al., 2014).

In this study, we integrate a *generic* crop phenology and allocation module based on the agronomical model – STICS, which has been extensively validated as a generic crop model to simulate various kinds of crops (e.g., wheat, maize, soybean, bananas) (Brisson et al., 1998, 2002) – into the carbon-water-energy LSM ORCHIDEE (Krinner et al., 2005), resulting into an Agro-Land Surface Model, ORCHIDEE-CROP (at version v0, hereafter as ORCHIDEE-CROP, <https://forge.ipsl.jussieu.fr/orchidee/wiki/>

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referred to as mosaic vegetation) which can have any size, generally given by the spatial resolution of climate forcing data. All PFTs that co-exist within a grid cell share the same climate forcing but different carbon, energy and water dynamics, due to their specific parameterizations. The sum of fluxes from the different PFT tiles is averaged before being given to the atmospheric model, in case of coupled simulations.

### 2.1.1 Crop development stages and phenology in ORCHIDEE-CROP

A thermal index (degree-day) adjusted for photoperiodic and vernalization effects according to crop types, controls the developments of temperate crops such as winter wheat and maize considered here. Seven development stages are sequentially simulated for crop growth and grain filling in the crop module same to STICS (in detail see Fig. 1 in Brisson et al., 1998). The timing and duration of each stage is calculated based on development units, describing physiological requirements of crops. These development units are calculated just as in STICS as growing degree days weighted by limiting functions to account for photoperiodism (e.g., winter wheat and soybean) and vernalization (e.g., winter wheat). Vernalization requirement is defined as a given number of vernalizing days (JVC) since the crop germination, and requires a minimum of 7 vernalizing day. The vernalizing value of a given day (JVI) is a function of air temperature. The vernalization status (RFVI) for the vernalization sensitive crop increases gradually to reach one when the vernalization requirement is met (Eq. S1 in the Supplement). The photoperiodic slowing effect, RFPI, is determined by two photoperiod thresholds, PHOBASE and PHOSAT, for photoperiodic crops. In the case of short-day crop, the PHOBASE is higher than PHOSAT, whereas in the case of long-day crop, the PHOBASE is lower than PHOSAT. The current photoperiod PHOI is calculated on the basis of calendar days and latitude (Sellers, 1965) (Eq. S2). Transition between stages occurs when threshold values of development units are reached, which are specific to different crops or cultivars but also depend upon management intensity and local climate. Using generic terms for the various stages of plant development makes it pos-

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sible to simulate different kinds of crops if crop-specific parameter values are provided (Bassu et al., 2014; Brisson et al., 2002; Valade et al., 2014).

Crop emergence occurs during the sowing-emergence stage, divided into a phase of seed germination and a phase of epicotyl extension. Germination occurs when the sum of degree-days, using the soil temperature (TSOL) at the sowing depth (PROFSEM), reaches a given threshold (STPLTGER) with a condition on soil dryness (Eq. S3). The growth rate of the epicotyl is assumed to be a logistic function depending on soil temperature and water status at the sowing depth (Eq. S4). Crop emergence occurs when the elongation of epicotyl > planting depth (PROFSEM). The actual density of emerged plants is calculated from the initial sowing density, a fixed parameter, considering the lack of germination and the death of a fraction of young plants due to unsuitable soil moisture (humectation or drought) and/or to thermal time deficit (Brisson et al., 2008). From emergence to physiological maturity, the temporal evolution of LAI is calculated in the crop module as the net balance between leaf growth and senescence. The daily growth rate of LAI (DELTAI) is calculated based on a logistic function of development units ( $DELTAI_{dev}$ , related to different development stages) multiplied by an effective crop temperature, an effective plant density which takes the inter-plant competition into account, and stress functions ( $DELTAI_{stress}$ ) related to water and nitrogen limitations (Eq. S5) (Brisson et al., 1998). The senescence of LAI depends upon the evolution of temperature and leaf lifespan as a function of leaf development and stresses (e.g., water stress). Consequently, senescence of LAI is updated each day (Brisson et al., 2008).

### 2.1.2 Photosynthesis, carbon allocation and yield

In ORCHIDEE-CROP, photosynthesis is calculated with the equations of ORCHIDEE (Krinner et al., 2005) based on the Farquhar leaf photosynthesis model for C3 crops (Farquhar et al., 1980) and on the model developed by Collatz et al. for C4 crops (Collatz et al., 1992). In both cases, photosynthetic rate is the minimum of the Rubisco-limited rate of CO<sub>2</sub> assimilation and the electron transport-limited rate of CO<sub>2</sub> assim-

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ilation, whose maximal values are model parameters ( $V_{cmax}$  and  $V_{jmax}$ , respectively). These two parameters can be calibrated using for instance leaf-level measurements for different kinds of crops and varieties.

In ORCHIDEE, the carbon allocation model common to all PFTs is adapted from Friedlingstein et al. (1999) and accounts for 8 biomass compartments (leaves, roots, fruits/harvested organs, reserves, aboveground sapwood, belowground sapwood, aboveground heartwood, belowground heartwood) for natural trees, and considers 5 carbon pools for grass and crop PFTs (leaves, roots, fruits/harvested organs, reserves, and aboveground sapwood). The fractions of newly formed assimilates or reserves allocated to these pools are parameterized as a function of soil water content, temperature, light, and soil nitrogen availability.

In ORCHIDEE-CROP, we modified the carbon allocation scheme of the two crop PFTs to reconcile the calculations of leaf and root biomass and grain yield (fruits/harvested organs) described by the phenology and LAI development parameterizations described in Sect. 2.1.1. Specifically, the daily increment of leaf biomass for crops,  $\Delta_{leaf\_m}$ , is calculated by dividing the daily change of LAI,  $\Delta_{LAI}$  by water and nitrogen stress factor-weighted specific leaf area (sla) (Brisson et al., 2008) as given by:

$$\Delta_{leaf\_m} = \Delta_{LAI}/sla \quad (1)$$

The daily increment of root biomass is determined by the daily total biomass increment and a dynamic belowground-to-total biomass partition coefficient, which depends on root development through a normalized root development unit. After the start of the grain filling stage, the quantity of dry matter accumulation in grains is calculated by using a variable “harvest index” function that determines the fraction of the daily increment of total biomass progressively allocated to grain filling. This “harvest index” function increases linearly with time from the start of grain filling to the physiological maturity of crop (when crop is harvested), restricted by an upper limit. The effects of extreme temperature impact the grain filling process and can stop carbon filling of har-

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vested organs as described by (Eq. S6) (Brisson et al., 2008). The remaining daily net primary production from ORCHIDEE, once allocation into leaf, root and grain biomass is performed (the latter occurring only after the start of the grain filling phase) is allocated to the stem compartment to conserve mass. In this case, this stem “residual” compartment denotes in fact both the actual stem biomass and additional reserves. At harvest, a small part of carbon (with the same amount to planted seeds) is moved from harvested organs to the reserves pool. This mimics the amount of carbon for seeds needed for the next crop season.

In ORCHIDEE-CROP the priority of carbon allocation to different compartments was changed to be consistent with the growth development phases derived from STICS. In vegetative stages, the leaf and root have the highest priority. In cases the NPP supply cannot satisfy the leaf and root biomass demand, no carbon is allocated to stems and the required amount for leaf and root growth is removed from the reserves. If the extreme case occurs in which the reserves are not sufficient, the amount of NPP allocated to leaf and root is reduced in the proportion of the shoot/root ratio (yet no carbon being allocated to stem). However, in such extreme cases, consistency between LAI and leaf biomass is lost. Conversely, during the reproductive stage, carbon allocation is prioritized to grain filling and leaf biomass, followed by stem and root allocation in case of remaining NPP. If the NPP available after the grain demand is satisfied is not sufficient to meet the allocation to grain, carbon is remobilized from stem and root (the reserve pool was used out before reproductive stages) according to a fixed shoot/root ratio.

### 2.1.3 Soil moisture limitation on plant growth

Water limitation for crop development and biomass production is accounted for through a water stress index, ranging in the interval [0–1], which is calculated from ORCHIDEE and applied to reduce leaf growth and accelerate leaf senescence rates. The water uptake function in ORCHIDEE is based on the assumption that the vertical root density profile is exponentially decreasing with depth (Krinner et al., 2005) and that water

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uptake is a function of root zone extractible water weighted by this root profile. Below a fixed root zone integrated relative water content threshold of 0.5, the ORCHIDEE stress index value decreases from 1 (no stress) to zero (wilting point), and the stress index is used as a multiplier of both  $V_{cmax}$  and stomatal conductance, acting to decrease both gross primary productivity and transpiration.

Two soil hydrological schemes (the 2 layer soil scheme, referred as 2LAY hereafter, and the 11 layer soil diffusion scheme, referred as 11LAY hereafter, in detail see Guimberteau et al., 2014) can be used alternatively in ORCHIDEE to calculate soil moisture, and all dependent ecosystem state variables. Relative root extractible soil moisture is computed by each hydrological scheme, as the mean relative soil moisture over the different soil layers, weighted by the fraction of roots within each layer (Krinner et al., 2005). The stress index defined as above is then calculated based on relative root extractible water, which differs between the 2LAY and the 11LAY versions. Application of water irrigated is not taken into account in this study. The typical exponential (and static) root profile assumed for grass and crop PFT in ORCHIDEE assumes that ~ 65 % of the roots are above 20 cm. This root distribution profile is different from the one that was used in STICS where only fewer roots were assumed in the upper 20 cm of soil and more below (Brisson et al., 2008; Gervois et al., 2004). But in ORCHIDEE-CROP we keep the root profile as parameterized in ORCHIDEE.

#### 2.1.4 Simplified nitrogen limitation and fertilization effects

Nitrogen fertilization allows to increase crop productivity and LAI, which consequently impacts crop phenology, carbon allocation and turbulent fluxes exchanged with the atmosphere (Mueller et al., 2012). ORCHIDEE-CROP is currently unable to account for dynamic nitrogen stress within the crop growing season due to the lack of an explicit parameterization of nitrogen processes and nitrogen-carbon interactions. We thus defined a simple nitrogen limitation index (innlai) expressed as a parameter ranging from 0 (the maximum limitation of nitrogen) to 1 (without nitrogen limitation). To account in a very simple manner for the effects of nitrogen fertilization on plant productivity, we

introduce an additive nitrogen response,  $N_{\text{add}}$ , of photosynthetic parameters,  $V_{\text{cmax\_opt}}$  and  $J_{\text{max\_opt}}$ , using the following equation:

$$N_{\text{add}} = 1 + N_{\text{max}} - N_{\text{max}} \times 0.75^{(N_{\text{fert}}/30)} \quad (2)$$

Where  $N_{\text{max}}$  is the maximum additive effects of nitrogen fertilization during growing season,  $N_{\text{fert}}$ , on the photosynthetic parameters (in detail see Chang et al., 2015). The  $N_{\text{max}}$  is a PFT-specific parameter that can be calibrated by the observed additive nitrogen fertilization effects on plant productivity (e.g., using field trials). This simple function allows us to estimate impacts of different levels of nitrogen fertilization on crop productivity (Chang et al., 2015).

## 2.2 Simulation set-up

### 2.2.1 Site description

We tested ORCHIDEE-CROP for winter wheat and maize at 7 eddy-covariance sites of the CarboEurope-IP project (<http://www.carboeurope.org/>). These sites span different climatic conditions (Table 1 and Fig. S1 in the Supplement). These sites recorded meteorological 1/2 hourly variables necessary to run ORCHIDEE-CROP, as well as  $\text{CO}_2$  fluxes (NEE), and latent and sensible heat. The NEE 1/2 hourly data were gap-filled and partitioned into gross productivity (GPP) and ecosystem respiration (TER) using the CarboEurope-IP methodology (Moffat et al., 2007; Papale, 2006; Reichstein et al., 2005). Management information (e.g., sowing and harvest date, irrigation and fertilization) and crop development monitoring data (e.g., LAI, aboveground biomass (AGB) and crop yield) were available at each site and used either for parametrization (sowing date, fertilization) or evaluation purpose. The geographic locations, climate regimes and management information are provided in Tables 1 and 2 and Fig. S1. More details about the 7 sites can be found in (Kutsch et al., 2010; Vitale et al., 2007).

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## 2.2.2 Climate forcing data and atmospheric CO<sub>2</sub>

At each site, meteorological forcing measured on the top of each flux tower on a half-hour time step, was directly used as model input, including air temperature, precipitation, wind speed, atmospheric water vapor pressure, shortwave and longwave incoming radiation, long-wave incoming radiation, mean near-surface atmospheric pressure. Annual CO<sub>2</sub> atmospheric concentration is prescribed from background atmospheric measurements. Because of gaps in meteorological data caused mainly by instrumentation malfunction, we reprocessed them using standardized procedures of gap-filling and quality control (Moffat et al., 2007; Papale, 2006). A significant source of systematic errors when comparing modeled and observed fluxes is the lack of energy balance closure in the eddy covariance data (Foken, 2008). Our evaluation revealed that there are obvious problem regarding the energy balance closure in the eddy covariance observations on these crop sites, with the energy closure rate ranging ~ 80.6–86.3% (e.g., Fig. S2). We performed corrections of daily LE and *H* measurements similar to Twine et al. (2000) and Jung et al. (2011), which preserve the Bowen ratio:

$$E_{\text{corr}} = \alpha \times E_{\text{uncorr}} = (R_n - G)/(H_{\text{uncorr}} + LE_{\text{uncorr}}) \times E_{\text{uncorr}} \quad (3)$$

where, *E* is either LE or *H* flux,  $\alpha$  is a daily correction factor,  $R_n$  and *G* is the net radiation and ground heat storage, respectively. In our correction we do not consider the ground heat storage due to the lack of observations. Although the magnitude and causes of energy balance imbalance likely vary among sites and across time scales (Barr et al., 2006; Franssen et al., 2010), this simplified approach can correct the energy balance closure and yield consistent energy fluxes with other independent estimates (Jung et al., 2011).

## 2.2.3 Simulation experiments

A set of simulations were performed for each crop-site (in detail see Table 1), using STICS (JavaStics-v11, <http://www6.paca.inra.fr/stics/>), ORCHIDEE and ORCHIDEE-

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CROP, respectively (in detail see Table 3). Observed climate data and crop type at each site were used to drive the models (in ORCHIDEE, winter wheat is assigned the C3 crop standard parameters and maize the standard C4 crop ones). The same mean soil depth and soil water holding capacity were prescribed for the 7 sites, averaged from the Harmonized World Soil Database (HWSD), <http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/>. At each site with rotation, we selected one year of observation during which winter wheat or maize was cultivated. The sowing date was prescribed to the model for each crop-site according to the management data (Table 2), but the harvest date was calculated by the model. The observed nitrogen fertilization and irrigation information for each crop-site were used in STICS experiment STI-WN (Tables 2 and 3). In STICS, the applied irrigation and nitrogen fertilization can be introduced into the model and are involved into the water balance and nitrogen transformation modules, respectively, from the irrigation and fertilization calendar (Brisson et al., 2008).

All simulations based on ORCHIDEE and ORCHIDEE-CROP started from an equilibrium state of carbon pools with climate obtained with a model spin-up. For this spin-up, site-specific meteorological 1/2 hourly data was repeatedly cycled for 300 years to force ORCHIDEE and ORCHIDEE-CROP until the soil water reached steady state (data not shown). Then, simulations were conducted for the period of evaluation, starting with initial conditions at the end of model spin-up. Notably, C input from manure input is not taken into account in this study.

The same cultivar (represented by the parameters of “Soissons” and “DK250” varieties in STICS for winter wheat and maize, respectively), rather than site-year specific varieties, choice was made in the model at all sites for winter wheat and maize, respectively (see Table 3). This may lead to some discrepancies between simulated and observed values, but our main purpose is to evaluate the improvements achieved by ORCHIDEE-CROP in a generic way, without having to calibrate the model for each site. Sensitivity tests were conducted to evaluate the effects of nitrogen limitation and water

stress on crop development, carbon and energy balances. The detailed ensemble of experiments is shown in Table 3.

### 2.3 Metrics for evaluating model performance

Three metrics were used to evaluate the model-data agreements at daily resolution for different fluxes (NEE,  $H$ , LE) and for LAI, AGB and grain yield biometric variables, at the different crop-sites where these observations are available.

First, we calculated the index of agreement (IOA) (Willmott et al., 1985), given by

$$IOA = 1.0 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (4)$$

where  $P_i$  is modelled data,  $O_i$  is observed data,  $\bar{O}$  is observed mean and  $n$  is the number of data. The IOA, with values ranging from 0.0 to 1.0, is more sensitive than correlation-based metrics to differences in the observed and modelled means and variances (Willmott et al., 1985).

We also calculated the Pearson's product-moment correlation coefficient for different sites. This metrics estimates the proportion of total variance in the observed data that can be explained by model, given by

$$r = \frac{\sum_{i=1}^n (P_i - \bar{P})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^n (P_i - \bar{P})^2} \sqrt{\sum_{i=1}^n (O_i - \bar{O})^2}} \quad (5)$$

where  $P_i$  is modelled data,  $O_i$  is observed data,  $\bar{P}$  is the modeled mean,  $\bar{O}$  is observed mean, and  $n$  is the number of data.

Third, the root mean square error (RMSE) and normalized root mean square error (NRMSE) were used to quantify the model-observation agreement in absolute terms,

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expressed as:

$$\text{RMSE} = \sqrt{\sum_{i=1}^n (P_i - O_i)^2 / n} \quad (6)$$

and

$$\text{NRMSE} = \sqrt{\sum_{i=1}^n (P_i - O_i)^2 / n / (O_{\max} - O_{\min})} \quad (7)$$

5 where  $P_i$  and  $O_i$  is modelled and observed data, respectively, and  $n$  is the number of data.

### 3 Results

#### 3.1 Crop phenology, plant development stages and productivity

10 Comparison of the seasonal evolution of observed and modelled LAI for winter wheat and maize at different sites is shown in Fig. 2. The modelled seasonality of LAI is markedly improved by ORCHIDEE-CROP (ORC-CP1, Table 3) compared with ORCHIDEE, for both winter wheat and maize. The correlation coefficient between observed daily LAI and modelled daily LAI show a marked ( $p < 0.05$ ) increase from ORCHIDEE to ORCHIDEE-CROP (ORC-CP1) from  $0.44 \pm 0.22$  to  $0.83 \pm 0.17$  for winter wheat and from  $0.64 \pm 0.22$  vs.  $0.79 \pm 0.10$  for maize. The IOA increases from  $0.47 \pm 0.11$  to  $0.82 \pm 0.12$  (winter wheat) and from  $0.57 \pm 0.15$  to  $0.85 \pm 0.08$  (maize) with a significant decrease of RMSE ( $2.71 \pm 0.49$  vs.  $1.12 \pm 0.36$  and  $2.06 \pm 0.86$  vs.  $1.04 \pm 0.31$  for winter wheat and maize, respectively) (Fig. 2, Table 4). Despite its overall good performance for LAI, ORC-CP1 (under moderate nitrogen limitation to leaf growth) cannot



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reproduce the amplitude of observed LAI within the measurement uncertainty (personal communications with PIs, 2014) at a few sites (Fig. 2). For example, maximum LAI is underestimated by 49 and 28 % for winter wheat in FR-Gri and FR-Lam, respectively. Reducing the nitrogen limitation for leaf growth (ORC-CP3) at these two sites can improve the modelled maximum LAI and bring it in agreement with the observations (Fig. S3, Table 4). The modelled growing season length (defined as the period going from crop sowing to harvest) by ORC-CP1 for all crop-sites is in good agreement with the observations (with IOA = 0.96 and RMSE = 25.4 days) (Fig. 3).

Along with the accurately simulated timing and amplitude of LAI, the seasonal evolution of aboveground biomass (AGB) gets improved in ORCHIDEE-CROP (ORC-CP1) compared with ORCHIDEE for both winter wheat and maize, except at BE-Lon for winter wheat and at NL-Lan for maize (Figs. 4 and 5). In general, the bias of modelled AGB is attributable to the bias of modelled LAI, as indicated by a significant ( $p < 0.005$ ) relationship between them for all crop-sites (Fig. S4). However, the daily change rate of above-ground biomass in the late growing season between the start of grain filling and yield harvest is systematically and significantly ( $p < 0.05$ ) underestimated for both winter wheat (change rate of AGB underestimated by 36–74 %) and maize (by 18–70 %), especially at the sites where LAI is underestimated (e.g., winter wheat at FR-Gri and FR-Lam) (Figs. 2, 4, and S5). In the reality, the decrease in above-ground biomass does not start until harvest (Fig. 4).

ORCHIDEE-CROP (ORC-CP1) can capture the timing of grain filling and yield harvest well comparing to the observations and STICS simulations (Fig. S6). Comparisons of modelled and observed crop yields for winter wheat and maize in FR-Aur and FR-Lam show a  $\sim 19$ –30 % underestimation of crop yields in ORC-CP1 without fertilization (Fig. 6), comparing to a good match (NRMSE = 8.8 %) between STICS with real fertilization (STI-WN) and observations (Fig. S6). However ORCHIDEE-CROP with real fertilization (ORC-CP4) can produce a better estimation of crop yields for these two sites than ORCHIDEE-CROP without fertilization (ORC-CP1), leading to a  $\sim 50$  % reduction in NRMSE (47 vs. 23 % for ORC-CP1 and ORC-CP4) (Fig. 6). Considering

the measurement uncertainties of FR-Aur and FR-Lam for crop yields (personal communications with PIs, 2014), ORCHIDEE-CROP with the simple nitrogen fertilization parameterization on crop productivity generally conserves reasonable performance compared to STICS that has a full-fledge nitrogen cycle, to capture both the timing and amplitude of crop yields.

### 3.2 CO<sub>2</sub> and energy fluxes

ORCHIDEE-CROP has a more realistic simulated seasonality and amplitude of NEE at most of the winter wheat sites than ORCHIDEE (significant increase of IOA and  $r$  and decrease of RMSE from  $2.9 \pm 0.2$  of ORCHIDEE to  $1.9 \pm 0.5 \text{ g C m}^{-2} \text{ day}^{-1}$  of ORC-CP1) and at the maize sites in humid regions (Figs. S1 and 7). Along with leaf area development (LAI) during the growing season, the model produces a CO<sub>2</sub> sink until shortly before harvest, when most leaves are senescent and crop photosynthesis cannot compensate for respiration, which is consistent to observations (Fig. 7). ORCHIDEE-CROP can also capture the observed peak of CO<sub>2</sub> release to atmosphere shortly (ranging 10–20 days, Fig. 7) after harvest for both winter wheat and maize due mainly to the pulse of litter decomposition.

However, there is a mismatch between the simulations and observations regarding the temporal evolutions of NEE for winter wheat in BE-Lon, with a weaker and earlier termination of CO<sub>2</sub> uptake in the model (Fig. 7). The underestimated LAI and earlier cessation of crop growth in ORC-CP1 at this site result into a negative bias of GPP during the late growing season ( $\sim 170$  days after sowing) (Figs. 2 and S7), which contributes to the underestimation of NEE uptake during the same period (Figs. 7 and S8). Notably, ORC-CP1 overestimates the NEE peak uptake of CO<sub>2</sub> for maize at sites with drier climate regimes in Europe (e.g., FR-Lam and IT-Bci). The overestimation of NEE at these summer-dry sites is probably mainly ( $\sim 68$ – $85$  % of explained variance as revealed by a generalized linear model) caused by the overestimation of GPP rather than by an underestimation of ecosystem respiration in ORC-CP1 (Figs. S7 and S8). Further analysis shows a much higher ( $p < 0.05$ ) rate of GPP per unit LAI in ORC-

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CP1 than observed at these southern European maize sites (Fig. S9). Notably, the ORCHIDEE-CROP with 11LAY hydrological scheme (ORC-CP5) improves the modelled NEE largely for maize at these sites, with a  $\sim 40\%$  decrease in NRMSE (Fig. 7).

Despite the improved seasonality of  $H$  for most of the crop-sites over Europe (Fig. S10), ORCHIDEE-CROP with 2LAY hydrological scheme generally overestimates  $H$  for winter wheat sites especially in the early- and mid-growing season (from sowing to  $\sim 160$ – $200$  days after sowing) and shows a more realistic simulation of  $H$  for maize sites (NRMSE of  $\sim 9$ – $13\%$ ). The overestimation of  $H$  at wheat sites occurs during the early- and mid-growing season (Fig. 8) when plants grow slowly with low canopy cover, and it is partly attributed to the underestimation of soil water content in top soil during that period (data now shown) or to insufficiently deep roots prescribed in the model. Notably, the ORC-CP5 with 11LAY soil hydrological scheme, which has a more realistic representation of soil water infiltration after rain and allows to simulate the vertical profile of soil moisture with desiccation of the surface soil during dry episodes, improves the simulation of  $H$  during this period, with NRMSE being brought down from  $\sim 7$ – $10\%$  in ORC-CP1 to  $\sim 5$ – $8\%$  in ORC-CP5 (Fig. 8). Notably, however, the 11LAY hydrological scheme usually overestimates the bare soil evaporation (data not shown), which will result in drier top soil condition and lead to higher  $H$ , which can partially explained the residual overestimation of  $H$ , even in ORC-CP5 (Fig. S10).

Consistent with the overestimation of  $H$  in ORC-CP1, ORC-CP1 generally underestimates LE among wheat sites (Fig. 9). A more realistic estimation of LE was observed in ORC-CP5 for majority of the crop-site simulations than ORC-CP1, showing a  $\sim 32\%$  decrease in NRMSE, except the winter wheat and maize simulation on DE-Kli site (Fig. 9). For the maize simulation at DE-Kli, ORC-CP5 overestimates the LE for  $\sim 110\%$  compared with the observations, while ORC-CP5 also overestimates the LE for wheat at DE-Kli during early- and mid-growing season (from sowing to 230 days since sowing). The overestimation of LE at this site for both winter wheat and maize is not likely to raise from the simulated LAI (good estimation, see above) nor from the systematic error in LE due to the effects of rainfall events (with daily rainfall  $\geq 3$  mm)

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(Figs. 8 and 9), but possibly some other factors, such as soil water holding capacity since in our study we used the same mean value among different sites despite the great difference. The slightly negative ( $\sim 16\%$  of RMSE) bias of LE simulated in ORC-CP5 at the wheat site FR-Lam during the peak leaf growth (during 210–250 days after planting) is due to an underestimation of LAI (Figs. 9 and 2). The slight overestimation of LAI for maize during periods of peak leaf growth (e.g., FR-Lam and NL-Lan) does not appear however to translate into a related overestimation of LE. This illustrates divergent responses of LE to changes of LAI between ORCHIDEE-CROP and the observations, which can be due to several factors, such as the parameterization of soil water stress (Fig. S11). The episodes of LE with low biases (during peaks of LE) are symmetrical to episodes of high  $H$  biases even though net radiation appears to be realistic, except for maize site IT-Bci in Italy (Fig. S12).

ORCHIDEE-CROP also has good ability to capture the spatial gradients of carbon and energy fluxes across different crop-sites in Europe. There are significant correlation coefficients between the observed and modelled GPP, NEE,  $H$  and LE, with  $r$  ranging from 0.75–0.90. Evaluation of IOA reveals a generally good agreement between the observed and modelled GPP, NEE,  $H$  and LE, with IOA ranging from 0.70–0.90 (Figs. 10 and S14–S16).

## 4 Discussion

### 4.1 General performance of ORCHIDEE-CROP

Marked improvement is achieved by ORCHIDEE-CROP comparing with ORCHIDEE for the simulated timing and amplitudes of plant developments (crop phenology) for winter wheat and maize at different sites investigated in Europe, showing agreements with observations within 65–95% (IOA) for biometric data and 78–98% (IOA) for all turbulent fluxes despite the lack of detailed crop management parameterization (Figs. 2–9), and the lack of an explicit calculation of nitrogen cycle in the croplands.

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Remarkably, ORCHIDEE-CROP has a good ability to reproduce the observed spatial gradients of carbon and energy fluxes across different climate zones in Europe, even using a fixed variety parameter setting among different sites, implying that these spatial gradients in biophysical and biochemical variables should be mainly climate driven rather than crop variety.

Improvements of crop phenology and carbon allocation lead to a general good match of the seasonality between modelled and observed AGB (with NRMSE of 11–54 %), yields, as well as carbon and energy fluxes (NRMSE of ~ 9.0–20.1 % and ~ 9.4–22.3 % for NEE and sensible and latent heat fluxes, respectively). Comparisons between the 2LAY and 11LAY hydrological schemes reveal that the 11LAY hydrological scheme can improve the modelling of soil water dynamics and hence lead to a better simulation of leaf growth and biochemical and biophysical variables, especially for the C4 crops planted in drier climate zones of Europe (Figs. 7–9), which in turn exerts great effects on the estimations of carbon balances in these regions, especially in context of the projected increasing climate variability and extremes (e.g., heat waves and drought events) (Beniston et al., 2007; Ciais et al., 2005; Stocker et al., 2013). Yet, parameterization of the water stress also depends on the profile of active roots, which is considered as fixed in all the versions of ORCHIDEE. An important direction for future improvement would be to have a more mechanistic parameterization of the root profile in the model.

Notably, the simple function of the additive nitrogen fertilization on crop productivity can lead to better agreement between the observed and modelled crop yields in ORCHIDEE-CROP, showing a ~ 50 % decrease in NRMSE (Fig. 6). The remaining discrepancies of simulated crop yield, and energy fluxes are generally within the observed uncertainties of measurement and energy closure. More importantly, ORCHIDEE-CROP has good ability to capture spatial gradients of crop-related fluxes variables, such as GPP, NEE,  $H$  and LE, across the studied sites in different climate zones of Europe (Figs. 10 and S14–S16). This is important for further application of this model using gridded data over Europe or even globe to investigate regional/global yield variations, and the interactions between croplands and climate system, while the cropland

has the potentially crucial climate feedbacks from the increasing intensification of agricultural activities as well as land changes (Pitman et al., 2009; Ramankutty et al., 2002; Sacks and Kucharik, 2011).

Failure of the model to capture the peak LAI at some crop-sites (e.g., winter wheat at FR-Gri and FR-Lam) under ORC-CP1 is at partly attributed to simplified representation of nitrogen limitation on crop growth and fertilization effects (in detail see Sect. 2). Alleviation of nitrogen limitation on leaf growth on these sites can improve the simulated amplitudes of LAI and capture the maximum LAI (Fig. S3). Actually, nitrogen limitation has a strong influence on the seasonal evolutions of crop growth (Fig. S3), and a more realistic representation of intra-seasonal nitrogen processes (results based on STICS with explicit nitrogen cycle) leads to a generally much better match between the modelled and observed LAI, except the NL-Lan for maize (Fig. S13).

Lack of modeling of the irrigation effects can also contribute some bias to the simulated LAI. Soil water stress on GPP and LE, impacting carbon allocation as well, play an important role in controlling crop developments, especially for summer crops (e.g., maize) planted in regions with dry summer episodes (Fig. S1, Table 1), where suffering intensive irrigation managements currently (Table 2) and possibly increase of irrigation requirements along with the climate warming (Döll, 2002). As illustrated by our results that lacking of irrigation managements in current version of ORCHIEE-CROP leads to a lower LAI in the later crop season at FR-Lam for maize in drier climate zones (Figs. 2 and 7), which in turn affect NEE and energy budget (Figs. 7–9). More importantly, the projected increasing drought stress for current cultivated croplands (Dai, 2012), with a more intense and longer lasting drought in drier climate zones (Davin et al., 2014; Trenberth et al., 2014), challenges the representations of soil hydro-logical processes and their interactions with other factors for existing Agro-LSMs.

## 4.2 Model limitation and uncertainty

The irrigation (as discussed above) effects on the crop developments and yields are not accounted for in this study, and it is yet important for investigating the historically

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long-term changes of crop yields during recently past decades, as the intensive human managements occur mainly since approximately middle of 20th century.

Several studies have shown that the spatial differences in crop managements contribute significantly to the tempo-spatial patterns of crop yields (Licker et al., 2010; Lobell and Field, 2007), besides the impacts of climate and soil fertility (Rosenzweig et al., 2013). Adaptive improvements in agricultural managements are regarded as a potential way to close the “yield gaps” in a relative sustainable manner for social-environmental system (Licker et al., 2010). How the model handles human management factors and their interactions with changing CO<sub>2</sub> and climate variations could have significant impacts on the simulations of crop evolutions and productions. Additionally, our current crop development module embodies a number of simplifications for the pest, diseases and weeds, which are assumed to be controlled. Besides, the extreme soil conditions (e.g., high salinity or acidity) are also crudely assumed to exert little effects on crop growth. All these can also introduce great uncertainties into the biophysical and biochemical simulations over croplands.

Therefore, explicit nutrition dynamics and a human management (e.g., irrigation, fertilization, application of new crop varieties, and pest management, etc.) module are with primary priority to be included in ORCHIDEE-CROP to improve our ability to understand and project the roles of croplands in food security, environmental footprints and ecosystem services in response to climate change.

## 5 Conclusions

ORCHIDEE-CROP, by integrating a *generic* process-based crop development and yield harvest module into a generic LSM – ORCHIDEE, allow us to assess the spatial and temporal dynamics of the important biophysical and biochemical interactions within the soil – vegetation – atmosphere continuum for temperate crops. Comprehensive evaluations show a generally good performance of ORCHIDEE-CROP in crop phenology, productivity as well as the biosphere–atmosphere carbon and energy exchanges in

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pan-Europe temperate crop sites covering different climate zones, even without the explicit human management module. Benefiting from the *generic* strategy in the crop module, ORCHIDEE-CROP can be widely applicable at regional and global scale. Moreover, with respect to future climate change, ORCHIDEE-CROP will allow us not only to predict the footprints of climate variations in food security, but also to simultaneously account for feedbacks of changes in crop behaviors to the atmosphere by coupling a general atmospheric circulation model (e.g., LMDz).

Nevertheless, a further improvement, especially the explicit nutrition dynamics and human management, is with primary priority and could significantly improve our ability to understand and predict the role of croplands in the biosphere–atmosphere continuum, in context of the increasing global demand for food and the urgent requirement to reduce the environmental footprints (Godfray et al., 2010; Mueller et al., 2012).

### Code availability

The ORCHIDEE-CROP is still undergoing development, especially for human management processes, and the code is modified frequently. Therefore, the codes are not ready for fully public access. However, the source codes of ORCHIDEE-CROP at an early version (v0) can be requested from X. Wu (xiuchen.wu@bnu.edu.cn) or N. Vuichard (nicolas.vuichard@lsce.ipsl.fr).

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**Table 1.** Basic geography and climate information for different crop sites.

| Crop type    | SiteID | Country    | MAP <sup>a</sup> | MAT <sup>b</sup> | Longitude | Latitude | Altitude (m) | KGCC <sup>c</sup> |
|--------------|--------|------------|------------------|------------------|-----------|----------|--------------|-------------------|
| Winter wheat | FR-Lam | France     | 702              | 12.55            | 1.24      | 43.49    | 180          | Cfb               |
|              | FR-Gri | France     | 579              | 11.5             | 1.95      | 48.84    | 125          | Cfb               |
|              | FR-Aur | France     | 700              | 12.9             | 1.11      | 43.55    | 242.5        | Cfb               |
|              | DE-Kli | Germany    | 674              | 7.1              | 13.52     | 50.89    | 478          | Cfb               |
| Maize        | Be-Lon | Belgium    | 800              | 10               | 4.74      | 50.55    | 165          | Cfb               |
|              | FR-Lam | France     | 702              | 12.55            | 1.24      | 43.49    | 180          | Cfb               |
|              | FR-Gri | France     | 700              | 11.5             | 1.95      | 48.84    | 125          | Cfb               |
|              | DE-Kli | Germany    | 674              | 7.1              | 13.52     | 50.89    | 478          | Cfb               |
|              | NL-Lan | Netherland | 786              | 9.8              | 4.9       | 51.95    | −0.7         | Cfb               |
|              | IT-Bci | Italy      | 900              | 15.5             | 14.96     | 40.52    | 20           | Csa               |

Note:

<sup>a</sup> MAP: mean annual precipitation;<sup>b</sup> MAT: mean annual temperature;<sup>c</sup> KGCC: the Koppen–Geiger climate classifications.

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**Table 2.** Management information for different crop-sites.

| Crop type           | SiteID | Year<br>(sowing) | Sowing<br>date | Irrigation (mm) |               |               |               |               | Fertilization (KgNha <sup>-1</sup> ) |               |               |   |  |
|---------------------|--------|------------------|----------------|-----------------|---------------|---------------|---------------|---------------|--------------------------------------|---------------|---------------|---|--|
|                     |        |                  |                |                 |               |               |               |               |                                      |               |               |   |  |
| Winter wheat        | FR-Lam | 2006             | 291            | 0               | 0             | 0             | 0             | 0             | 46.5                                 | 48.2          | –             | – |  |
|                     |        |                  |                |                 |               |               |               |               | (18 Jan 2007)                        | (4 May 2007)  |               |   |  |
|                     | FR-Gri | 2005             | 301            | 0               | 0             | 0             | 0             | 0             | 55.0                                 | 55.0          | –             | – |  |
|                     |        |                  |                |                 |               |               |               |               | (15 Mar 2006)                        | (14 Apr 2006) |               |   |  |
|                     | FR-Aur | 2005             | 300            | 0               | 0             | 0             | 0             | 0             | 50.0                                 | 40.0          | 33.5          | – |  |
|                     |        |                  |                |                 |               |               |               | (25 Jan 2006) | (23 Mar 2006)                        | (12 Apr 2006) |               |   |  |
| DE-Kli              | 2006   | 269              | 0              | 0               | 0             | 0             | 0             | 74.3          | 53.8                                 | 35.8          | 43.1          |   |  |
|                     |        |                  |                |                 |               |               |               | (8 Apr 2007)  | (4 May 2007)                         | (4 Jun 2007)  | (22 Jun 2007) |   |  |
| Be-Lon              | 2006   | 286              | 0              | 0               | 0             | 0             | 0             | 40.0          | 60.0                                 | 94.5          | –             |   |  |
|                     |        |                  |                |                 |               |               |               | (17 Mar 2007) | (12 Apr 2007)                        | (8 May 2007)  |               |   |  |
| Maize               | FR-Lam | 2006             | 121            | 25.0            | 33.0          | 27.8          | 18.0          | 44.0          | 91.0                                 | –             | –             | – |  |
|                     |        |                  |                | (13 Jun 2006)   | (3 Jul 2006)  | (15 Jul 2006) | (26 Jul 2006) | (10 Aug 2006) | (8 Jun 2006)                         |               |               |   |  |
|                     | FR-Gri | 2005             | 129            |                 |               |               |               |               | 140.0                                | –             | –             | – |  |
|                     |        |                  |                |                 |               |               |               |               | (9 May 2005)                         |               |               |   |  |
|                     | DE-Kli | 2007             | 118            |                 |               |               |               |               | 17.3                                 | 67.2          | –             | – |  |
|                     |        |                  |                |                 |               |               |               | (22 Apr 2007) | (13 Jun 2007)                        |               |               |   |  |
| NL-Lan <sup>a</sup> | 2005   | 138              | 0              | 0               | 0             | 0             | 0             | –             | –                                    | –             | –             |   |  |
| IT-Boi              | 2004   | 129              | 21.8           | 27.2            | 20.3          | 25.7          | 23.4          | 22.5          | 142.0                                | –             | –             |   |  |
|                     |        |                  | (24 Jun 2004)  | (2 Jul 2004)    | (15 Jul 2004) | (18 Jul 2004) | (20 Jul 2004) | (8 May 2004)  | (11 Jun 2004)                        |               |               |   |  |
|                     |        |                  | 22.1           | 19.3            | 22.9          | 22.1          | 15.           |               |                                      |               |               |   |  |
|                     |        |                  | (27 Jul 2004)  | (31 Jul 2004)   | (5 Aug 2004)  | (12 Aug 2004) | (21 Aug 2004) |               |                                      |               |               |   |  |

Note: <sup>a</sup> There is strong organic fertilization.

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**Table 3.** Description of the ensemble of simulations.

| Name of experiments | Description of experiments   | Irrigation | Nitrogen processes <sup>a</sup> | Soil water scheme <sup>b</sup> | Stlevdrp (GDD) <sup>c</sup> | Strdrpmat (GDD) <sup>d</sup> |
|---------------------|--|------------|---------------------------------|--------------------------------|-----------------------------|------------------------------|
| STI-NN              | STICS without fertilization during crop development <sup>e</sup>               | NO         | DY                              | –                              | 540/990                     | 750/600                      |
| STI-WN              | STICS with actual fertilization based on management records <sup>f</sup>       | NO         | DY                              | –                              | 540/990                     | 750/600                      |
| ORC-ST0             | Standard version of ORCHIDEE without crop development module, no fertilization | NO         | NO                              | LAY2                           | 540/990                     | 750/600                      |
| ORC-CP1             | ORCHIDEE-CROP with moderate nitrogen limitation, no fertilization              | NO         | NO, innlai = 0.5                | LAY2                           | 540/990                     | 750/600                      |
| ORC-CP2             | ORCHIDEE-CROP with high nitrogen limitation, no fertilization                  | NO         | NO, innlai = 0.2                | LAY2                           | 540/990                     | 750/600                      |
| ORC-CP3             | ORCHIDEE-CROP with low nitrogen limitation, no fertilization                   | NO         | NO, innlai = 0.9                | LAY2                           | 540/990                     | 750/600                      |
| ORC-CP4             | ORCHIDEE-CROP with moderate nitrogen limitation, real fertilization            | NO         | ND, innlai = 0.5                | LAY2                           | 540/990                     | 750/600                      |
| ORC-CP5             | Same to ORC-CP1, but with 11 layer soil hydrological scheme, no fertilization  | NO         | NO, innlai = 0.5                | LAY11                          | 540/990                     | 750/600                      |

**Note:**

<sup>a</sup> DY, with dynamic nitrogen processes, NO, without nitrogen processes, ND, without dynamic nitrogen processes but with a simplified additive nitrogen response of crop productivity to fertilization. For ORCHIDEE-CROP, we introduced a fixed nitrogen limitation factor for leaf growth (innlai, ranging 0.0–1.0) during the whole crop growing season.

<sup>b</sup> Two soil hydrological schemes (the 2 layer soil scheme, referred as 2LAY, and the 11 layer soil diffusion scheme, referred as 11LAY, in detail see Guimberteau et al., 2014) are available in ORCHIDEE and ORCHIDEE-CROP.

<sup>c</sup> The accumulated growing degree days (GDD) from crop emergence to start of grain filling for winter wheat (C3 crop) and grain (C4 crop), respectively.

<sup>d</sup> The accumulated growing degree days (GDD) from start of grain filling to crop mature for winter wheat (C3 crop) and grain (C4 crop), respectively.

<sup>e</sup> JavaStics (v11.0) used here was obtained from <http://www6.paca.inra.fr/stics>.

<sup>f</sup> The detailed crop managements for each crop-site were shown in Table 2.

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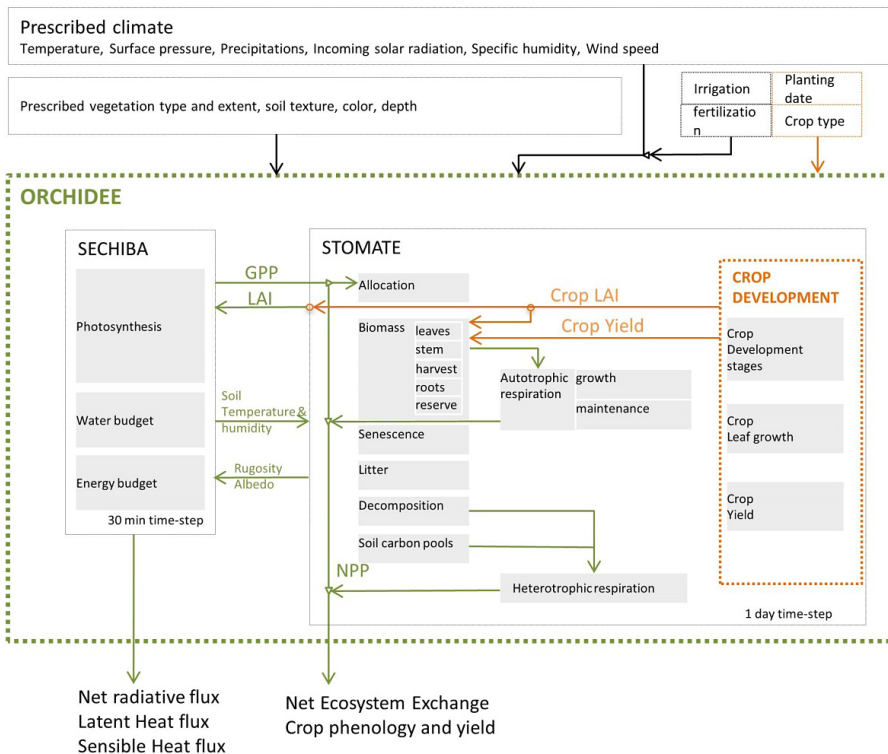
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**Table 4.** Comparisons between observations and different simulations.

| Crops        | SiteID | IOA     |         |         |         | <i>R</i>          |                   |                   |                   | RMSE (m <sup>2</sup> m <sup>-2</sup> ) |         |         | NRMSE (%) |         |         |         |         |
|--------------|--------|---------|---------|---------|---------|-------------------|-------------------|-------------------|-------------------|--|---------|---------|-----------|---------|---------|---------|---------|
|              |        | ORC-ST0 | ORC-CP1 | ORC-CP2 | ORC-CP3 | ORC-ST0           | ORC-CP1           | ORC-CP2           | ORC-CP3           | ORC-ST0                                | ORC-CP1 | ORC-CP2 | ORC-CP3   | ORC-ST0 | ORC-CP1 | ORC-CP2 | ORC-CP3 |
| Winter wheat | BE-Lon | 0.37    | 0.65    | 0.52    | 0.63    | 0.15              | 0.92 <sup>b</sup> | 0.96 <sup>c</sup> | 0.73              | 3.30                                   | 1.53    | 1.78    | 1.74      | 93.52   | 52.81   | 61.41   | 60.14   |
|              | FR-Lam | 0.48    | 0.88    | 0.67    | 0.88    | 0.30              | 0.79 <sup>a</sup> | 0.83 <sup>b</sup> | 0.86 <sup>b</sup> | 2.68                                   | 0.90    | 1.48    | 1.21      | 60.72   | 20.44   | 33.52   | 27.56   |
|              | FR-Gri | 0.66    | 0.87    | 0.63    | 0.97    | 0.74              | 0.96 <sup>c</sup> | 0.92 <sup>c</sup> | 0.97 <sup>b</sup> | 1.86                                   | 1.34    | 2.45    | 0.73      | 30.44   | 22.01   | 40.09   | 11.93   |
|              | FR-Aur | 0.40    | 0.95    | 0.77    | 0.75    | 0.51              | 0.95 <sup>b</sup> | 0.91 <sup>a</sup> | 0.89 <sup>a</sup> | 3.06                                   | 0.52    | 0.85    | 1.58      | 107.47  | 18.42   | 29.84   | 55.61   |
|              | DE-Kli | 0.46    | 0.74    | 0.56    | 0.62    | 0.49              | 0.55              | 0.47              | 0.56              | 2.68                                   | 1.31    | 1.17    | 2.07      | 101.02  | 49.26   | 44.06   | 77.96   |
| Maize        | DE-Kli | 0.65    | 0.89    | 0.64    | 0.81    | 0.77              | 0.80 <sup>a</sup> | 0.74              | 0.89 <sup>a</sup> | 1.66                                   | 1.05    | 1.94    | 1.90      | 35.78   | 22.62   | 41.93   | 40.94   |
|              | FR-Lam | 0.50    | 0.86    | 0.69    | 0.57    | 0.92 <sup>a</sup> | 0.76 <sup>c</sup> | 0.88 <sup>b</sup> | 0.55              | 2.46                                   | 1.00    | 1.31    | 2.58      | 74.95   | 30.42   | 40.08   | 78.75   |
|              | FR-Gri | 0.58    | 0.96    | 0.64    | 0.91    | 0.45              | 0.95 <sup>b</sup> | 0.92 <sup>b</sup> | 0.97 <sup>c</sup> | 2.04                                   | 0.68    | 2.07    | 1.34      | 44.69   | 14.86   | 45.32   | 29.43   |
|              | NL-Lan | 0.77    | 0.80    | 0.63    | 0.39    | 0.80              | 0.71              | 0.83 <sup>a</sup> | 0.45              | 0.79                                   | 0.89    | 1.34    | 2.52      | 24.82   | 27.98   | 42.28   | 79.18   |
|              | IT-Bci | 0.38    | 0.74    | 0.49    | 0.73    | 0.42              | 0.70 <sup>a</sup> | 0.84 <sup>a</sup> | 0.65              | 3.37                                   | 1.60    | 2.62    | 1.98      | 85.37   | 40.59   | 66.33   | 50.11   |

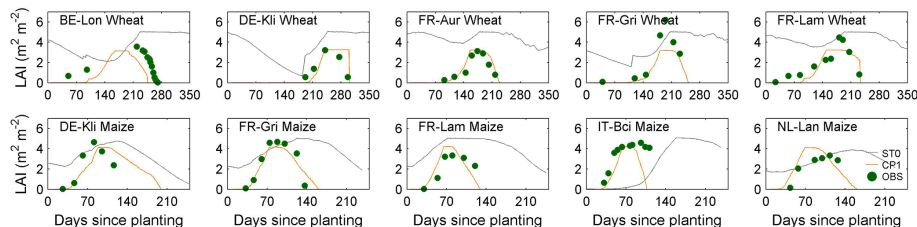
Note: IOA, index of agreement; *R*, Pearson's product-moment correlation coefficients; RMSE and NRMSE are the root mean square error and normalized root mean square error, respectively. <sup>a</sup>, <sup>b</sup> and <sup>c</sup> indicates statistically significant at 5, 1 % and 1 % level, respectively.



**Figure 1.** Model structures of the ORCHIDEE-CROP. The crop development module (based mainly on STICS, Brisson et al., 1998) is integrated into the STOMATE module of ORCHIDEE (Krinner et al., 2005). The crop development module simulated the phenology, developments and grain yields for crop PFTs. ORCHIDEE-CROP consists in the coupling of two modules. SECHIBA simulates the vegetation photosynthesis, water and energy budgets, STOMATE is a carbon module and calculates carbon allocation in different carbon pools and fluxes to the atmosphere.

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**Figure 2.** Temporal changes of daily leaf area index (LAI) since planting from observations (green dots), standard ORCHIDEE (ORC-ST0, grey line) and ORCHIDEE-CROP (ORC-CP1, orange line). The upper and lower panel shows the results for different sites of winter wheat and maize, respectively.

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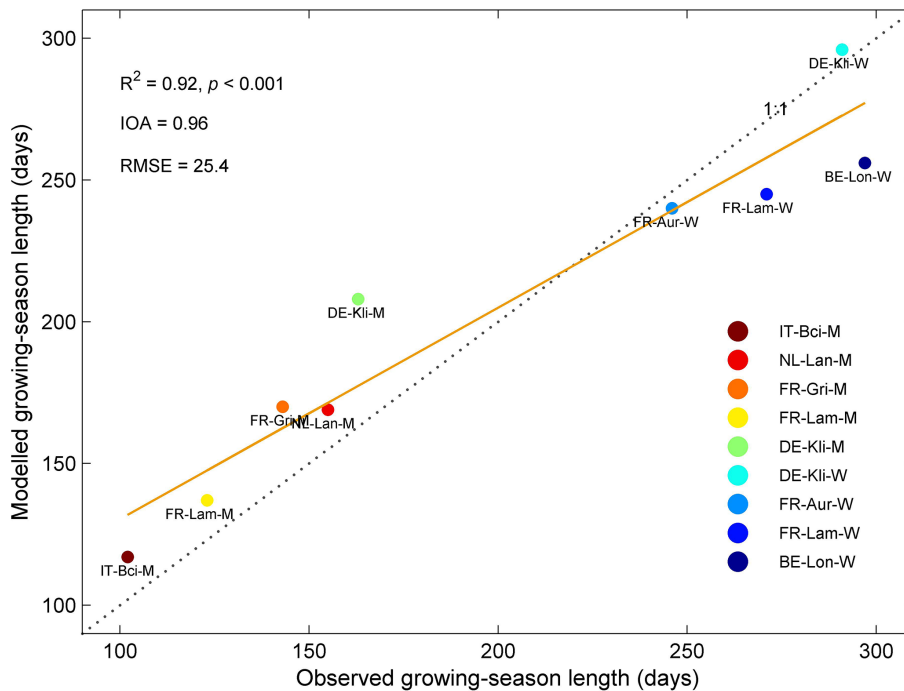
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**Figure 3.** Comparisons of the observed and modelled (ORC-CP1, in detail see Table 3) growing season lengths (from sowing to maturity) for winter wheat and maize in different sites. Different colors indicate data for different crop-sites.

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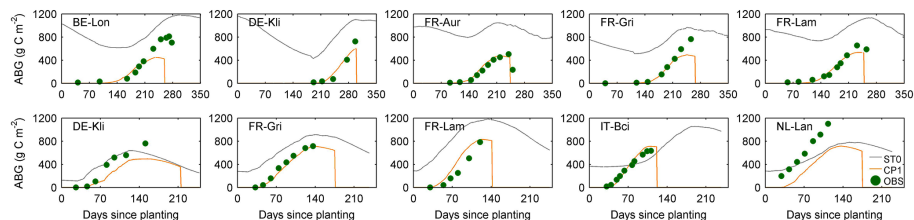
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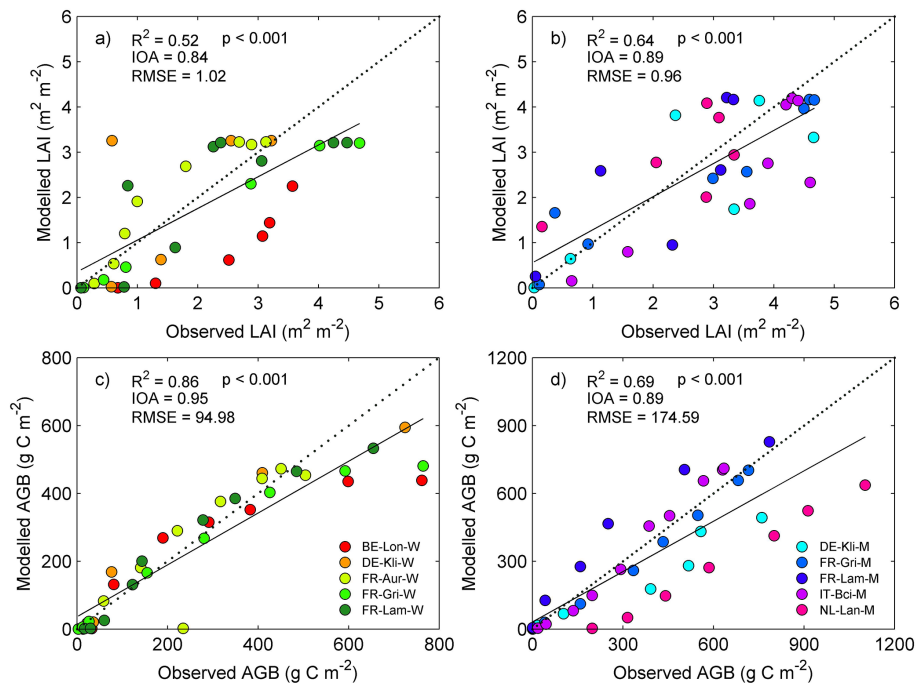
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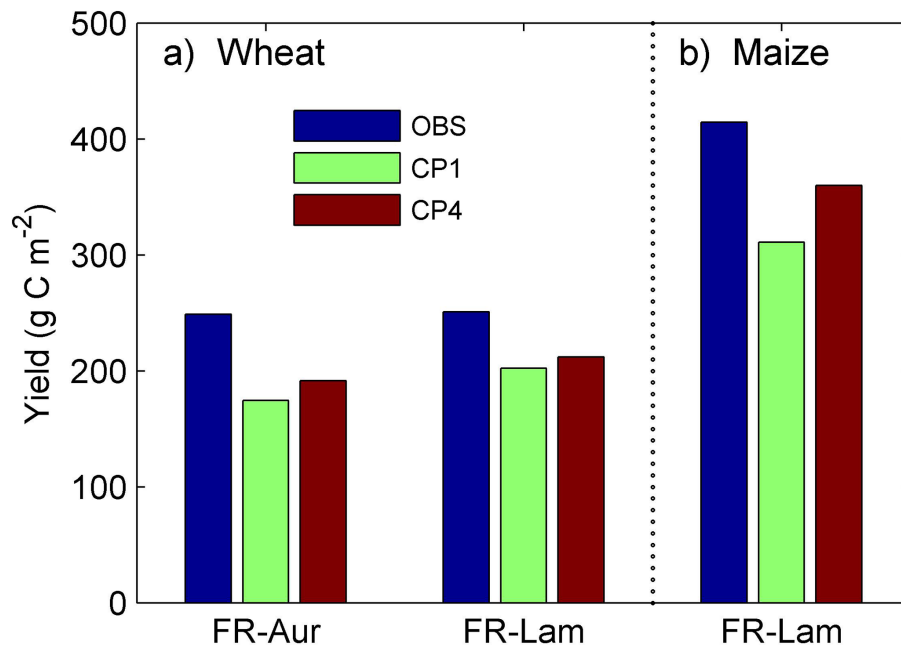


**Figure 4.** Comparisons of the observed (green dots) and modelled daily aboveground biomass from ORCHIDEE-CROP (ORC-CP1, orange line) and ORCHIDEE (ORC-ST0, grey line) for winter wheat and maize in different sites. The upper and lower panel shows the results for different sites of winter wheat and maize, respectively.

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**Figure 5.** Scatter plots of the modeled (ORC-CP1, in detail see Table 3) and observed daily LAI and aboveground biomass (AGB) for different sites of winter wheat (**a** and **c**) and maize (**b** and **d**), respectively. The units for RMSE of LAI and AGB are m<sup>2</sup> m<sup>-2</sup> and g C m<sup>-2</sup>, respectively. Different colors indicate different crop-sites with red, orange, light green, green and dark green for winter wheat (-W) at BE-Lon, DE-Kli, FR-Aur, FR-Gri and FR-Lam, respectively, and with light blue, medium blue, blue, purple and violet for maize (-M) at DE-Kli, FR-Gri, FR-Lam, IT-Bci and NL-Lan, respectively.



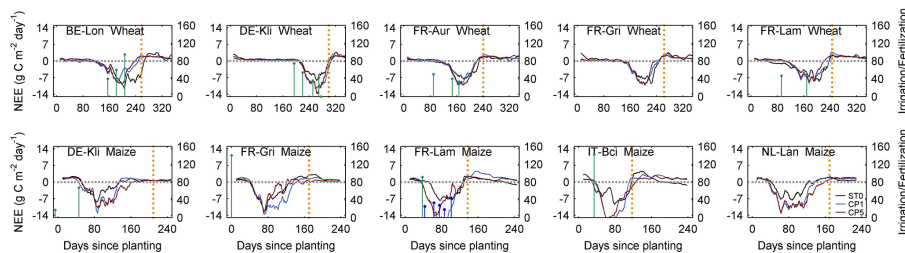
**Figure 6.** Comparisons of the observed (blue bars) and modelled (green bars for ORC-CP1 and brown bars for ORC-CP4, see Table 3) harvested crop yields in different sites for winter wheat (a) and maize (b).

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**Figure 7.** Temporal changes of daily net ecosystem exchanges (NEE) derived from observations (black line) and ORCHIDEE-CROP (ORC-CP1, blue line; ORC-CP5, brown line) since planting. The green and blue stems represent the fertilization ( $\text{kg N ha}^{-1}$ ) and irrigation (mm) events during the selected growing season. The dotted orange line indicates the harvest date since planting. The upper and lower panel shows the results for different sites of winter wheat and maize, respectively.

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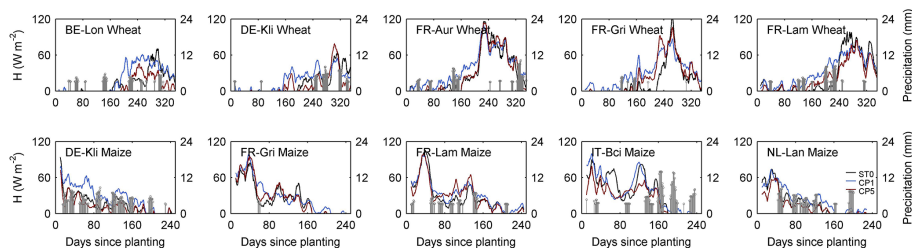
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**Figure 8.** Comparisons between the observed (black line) and modeled daily sensible heat fluxes ( $H$ ) from ORCHIDEE-CROP (ORC-CP1, blue line; ORC-CP5, brown line) for different crop-sites. The grey stems represent the relative large rainfall events (with daily summed rainfall  $\geq 3$  mm) during the modelled growing season. The upper and lower panel shows the results for different sites of winter wheat and maize, respectively.

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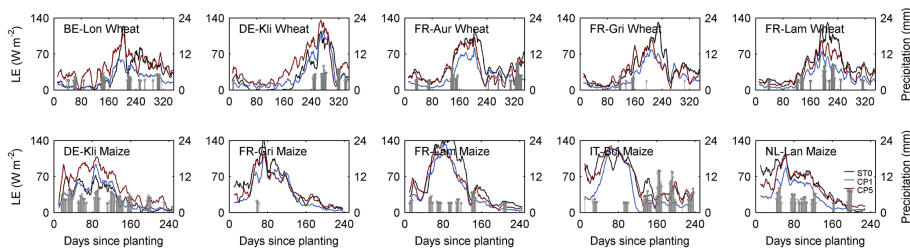
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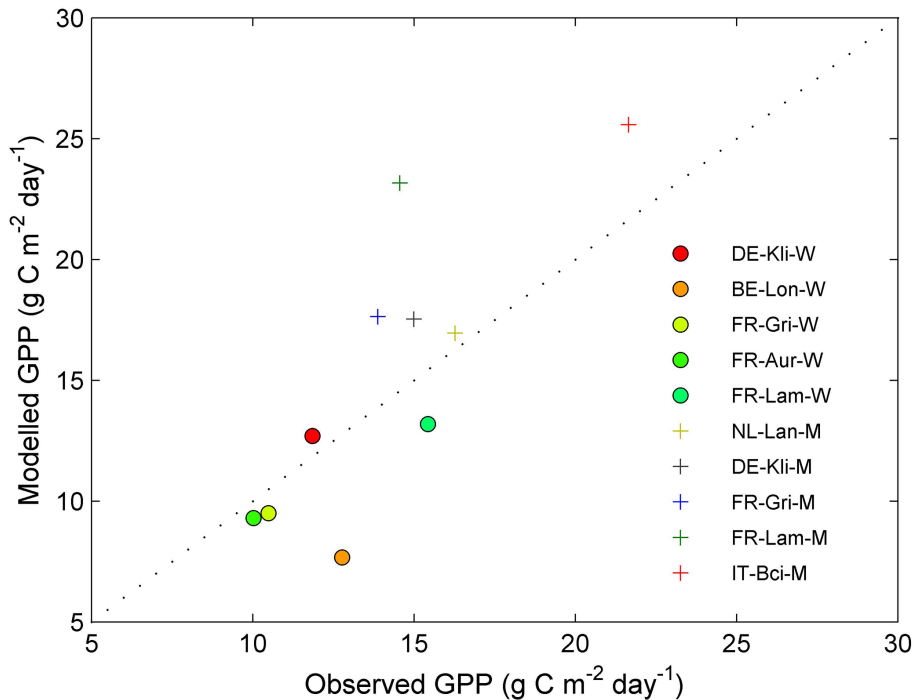




**Figure 9.** Same to Fig. 8 except for latent heat fluxes (LE).

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**Figure 10.** Comparisons between the observed and modelled (based on ORC-CP5) mean growing season GPP among different crop sites for winter wheat (circle, -W) and maize (cross, -M). Different colors indicate different sites.

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