Point-to-point response to reviewers’ comments

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1. *I have a concern about the advantage of the new model. Several models have been presented to simulate cropland processes (e.g., DNDC by Li et al., 1992; LPJmL by Bondeau et al., 2007; AgroIBIS by Kucharik et al., 2007; JULES-SUCROP by Van den Hoof et al., 2011). What are the characteristics and advantages of the model presented in this study? Please clarify the point in discussion.*

   Response: Thank you for your comments. Indeed, there are a lot of models are developed to simulate the croplands processes. All those models can be grouped into two categories: crop specific models (such as Crop-DNDC, STICS, etc.) and Agro-land surface models (such as, LPJml, JULES-SUCROP, and ORCHIDEE-crop). ORCHIDEE-crop is designed as an Agro-LSM, so here we discussed the progress of different Agro-LSMs, which can simulate both managed and natural vegetation dynamics interacting with climate change. Some of the existed DGVM crop modes are suffered from any/some of the following short-comings: a). adopted a simplification strategy for representing the growth dynamics of varied kinds of crops in some Agro-LSM (e.g., the CFTs in LPJml); b). model performance is limited to specific crops (e.g., Agro-IBIS for corn, soybean and wheat specifically) and/or regions (e.g., Agro-IBIS for Northern America specifically); and c). processes of crop growth and carbon allocation is not explicitly simulated but rather with some artificial approximations (e.g., the emergence start of crops and the initial carbon allocations in JULES-SUCROP is artificially fixed and the carbon allocations into of dry matter into different organs are also parameterized with fixed factors within different growth stages). Rather, the ORCHIDEE-crop is developed as an Agro-LSM by adopting a generic framework through integrating the crop processes of STICS into a DGVM model ORCHIDEE. Thus, managed and natural vegetation share the same fundamental biophysical and biochemical functions within the DGVM framework. ORCHIDEE-crop can simulate many different kinds of crops over the global with a generic crop development structure. The crop phenology, developments and carbon allocations during crop growth are with a relatively complete scope. The emergence, growth, maturity and senescence of crops are determined by climate conditions and some kinds of limitations (e.g., nitrogen limitation). The carbon allocations of dry matter into different organs are determined by specific component growth rates, which is dynamically determined by climate conditions and limiting factors. Additionally, crop processes were modelled differently within different DGVM crop models and it is the purpose of some MIP projects to compare model outputs and model skills.

2. *Page 4655 Abstract In abstract, you mentioned about the comparison with ORCHIDEEv196 but not with STICS. Please add some statements.*

   Response: In the revision, we add some statements for the comparison between the ORCHIDEE-crop and STICS.

3. *Page 4656 Line 17 "ressources" should be replaced by "resources".*

   Response: Done.

4. *Page 4657 Lune 21 "Incomplete" should be replaced by "incomplete".*

   Response: Done.

5. *Page 4662 Line 19 I could not understand the statement "If the NPP available after the grain demand is satisfied is not sufficient to meet the allocation to grain, ...".*

   Response: We checked this sentence and found that the latter "*grain*" should be leaf. Therefore, the sentence has been revised into "*If the NPP available after the grain demand is satisfied is not sufficient to meet the allocation to leaf,…*".

6. *Page 4665 Line 5 "long-wave incoming radiation" appears twice.*

   Response: we deleted the redundant one.

7. *Page 4668 Line 7 Results section should be, in general, described with the past tense.*

   Response: Done.

8. *Page 4672 Line 1 The simplified root distribution could also account, at least partly, for the discrepancy in LE. Is it correct?*

   Response: Yes, we agree with you completely. We include your suggestion into our discussion part for explaining the discrepancy in LE simulation.

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1. *The biggest deficiency in the approach is clearly the failure to include a mechanism for irrigation. This is mentioned in the process description only briefly on 4663. It would benefit the paper if this could be expanded somewhat to describe why irrigation was not included. Irrigation is not generally considered to be a difficult thing to include in a process model, with most models using simple rules where additional water is applied if topsoil moisture falls below some threshold. Given that water cycles and especially large-scale irrigation patterns have been shown to have significant impacts on regional climate in several recent studies, this seems like a surprising oversight in what is otherwise a very comprehensive treatment of crops in a land-surface scheme.*

   Response: Thank you Joshua for your valuable comments. ORCHIDEE-crop is built by integrating the detailed crop development and carbon allocation processes of STICS, a generic crop model, into the DGVM ORCHIDEE. There are two modules in the stardard ORCHIDEE (version Tag196): SECHIBA (simulating energy and water dynamics within the SPA continuum and plant photosynthesis, etc) and STOMATE (simulating carbon allocation, decomposition, vegetation dynamics, etc.). In ORCHIDEE-crop (V0 version), the crop development is driven by the thermal-hydro variables (e.g., soil temperature, water infiltration, soil moisture conditions, etc.) simulated in SECHIBA module. Both managed and natural vegetation share the same thermal-hydro dynamics within the same mosaic (something like a pixel with different vegetation types mixed together). Therefore, if we want to be rigorous we need to change the water and energy processes only on cropland, which is more complicated. It have been done now in a new version but the detailed estimation for that process was out of the main scope of this paper.

2. *I also have some further questions about the root distribution. Root biomass is accrued dynamically but as stated it seems that root depth and distribution is static, with 65% in the top 20cm. Is that correct?*

   Response: I agree with you that root dynamic is a key process for better representing the crop development and its interaction with water conditions. The water limitation effects on crop growth is estimated by the mean water condition within the root zone. In the current version, we did not consider the dynamic of root growth, but with a static distribution of root during the whole growing season, with 65% in the top 20 cm.

3. *Since the model considers winter wheat, it would be good to comment on whether/how cold temperature effects (leaf kill and full plant kill) are considered and (in the case where leaves are killed but he plant survives) whether/how this effects allocation during subsequent growth.*

   Response: Yes, you are right. Cold temperature during growing season (from planting to harvest) has important impacts on winter wheat growth. In ORCHIDEE-crop, the effects of cold temperature on winter wheat growth are different in different development stages. From planting to emergence, the cold temperature can impact the crop seeding emergence by both vernalization and thermal accumulation effect. Since emergence, the cold temperature can reduce or even stop (the cold temperature can lead to a no increment in daily LAI) the increment of LAI on a daily step and thus lead to changes in daily leaf growth (leaf growth is determined by both leaf growth increment and daily senescence dynamic) and hence other processes (e.g., photosynthesis, carbon allocations, etc.).

4. *It may not be in the scope of this paper, but I'm certainly very curious to know also how different the new scheme is in terms of large-scale factors that could affect climate feedbacks. Some integrated measure of surface albedo, total carbon budgets, etc. if possible, it would be good to add to the conclusion some statement about this. Does it greatly increase or decrease the land-surface climate feedback in any way that you expect to have implications for future IPSL coupled runs?*

   Response: This is really an important issue within the terrestrial-atmosphere interactions. As illustrated in previous literatures that the standard ORCHIDEE simulated crops (C3 and C4) as "super grass", with same phenology routines as grasses but different photosynthesis abilities. However, in ORCHIDEE-crop we integrated a generic crop module into ORCHIDEE and it simulated the crop phenology, development and carbon allocations based on explicit processes of crop development. The ORCHIDEE-crop can at least improve both the seasonality and magnitudes of LAI for different crops (as illustrated in our manuscript). Thus, ORCHIDEE-crop can improve the simulations of surface roughness, surface albedo, water, energy and carbon budgets for land surface (mixed with both natural and managed vegetation types). Therefore, an improvement in the land-surface climate feedbacks is reasonably expected for the future IPSL coupling.

5. *Small things. Some editorial work is needed to improve readability. For example, page 4659 line 10 "in the crop module same to STICS".*

   Response: We went through the manuscript carefully and made our presentation much clearer.

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

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Abstract:

The response~~s~~ of crops to changing climate and atmospheric CO_2 concentration ($[CO_2]$) could have large effects on food production, and impact carbon, water, and energy fluxes, causing feedbacks to the climate. To simulate the response~~s~~ of temperate crops to changing climate and $[CO_2]$, ~~that~~which accounts~~ing~~ for the specific phenology of crops mediated by management practice, we ~~present~~ describe 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 using~~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 seven~~7~~ winter wheat and maize sites in Europe. The specific ecosystem variables used in the evaluation are CO_2 fluxes (net ecosystem exchange (NEE)), latent heat, and sensible heat fluxes. Additional measurements of leaf area index (LAI), aboveground biomass and yield are used as well. Evaluation results revealed that ORCHIDEE-CROP (v0) reproduced~~s~~ the observed timing of crop development stages and the amplitude of the ~~pertaining~~ LAI changes. This is in contrast to ORCHIDEEv196 ~~in which~~where, by default, crops have

the same phenology ~~than~~ as grass. A ~~near~~ halving of the root mean square error for~~of~~ LAI from 2.38 ± 0.77 $\mathrm{m^2\ m^{-2}}$ to 1.08 ± 0.34 $\mathrm{m^2\ m^{-2}}$ was~~is~~ obtained ~~between~~ when ORCHIDEEv196 and ORCHIDEE-CROP (v0) were compared across the seven~~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 a NRMSE of ~ 9.0%–20.1% and ~ 9.4%–22.3% for NEE), and sensible and latent heat fluxes~~, respectively~~. The simulated yields for~~of~~ winter wheat and maize from ORCHIDEE-CROP (v0) showed a good match with~~to~~ the simulated results from STICS for three sites with available crop yield observations, where the~~with an~~ average NRMSE was~~of~~ ~8.8%. The model data mis~~t~~fit for energy fluxes were~~are~~ within the uncertainties of the measurements, which themselves showed an incomplete energy balance closure within the range 80.6%~~–~~–86.3%. The remaining discrepancies between the model~~l~~ed and observed LAI and other variables at specific sites were~~are~~ partly attributable to ~~unrealistic impossible~~ unrealistic representations of management events ~~from~~by the model. ~~In addition,~~ ORCHIDEE-CROP (v0) ~~is shown to have~~has the ability to capture the spatial gradients of carbon and energy-related variables, such as gross primary productivity, NEE, and sensible ~~heat fluxes~~ and latent heat fluxes~~,~~ across the sites in Europe, which is an important requirement for future spatially explicit simulations. Further improvement of the model, with an explicit parameterization of nutritional dynamics and ~~of~~ management, is expected to improve its predictive ability to simulate croplands in an Earth System Model.

Keywords: Crop model, ORCHIDEE-CROP, STICS, Crop yield, Energy balance~~s~~, Net ecosystem exchange~~s~~

Introduction

Croplands cover about ~~∼~~12% of the world 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 response~~s~~ of croplands to climate change ~~are~~ is expected to have significant, but uncertain, consequences for 1) global food production and 2) land surface water, carbon, and energy fluxes, which affect~~s~~ food security as well as regional climate and water res~~s~~ources (Bonan, 2008, 2001; Loarie et al., 2011; Rosenzweig et al., 2014).

Along with improving understanding of crop physiology to ~~improve~~ increase 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 have always pointed to ~~out to~~ ~~a~~the significant ~~contribution of~~effect 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 models have highlighted the uncertainties that are related to model structure, parameterization, and external drivers (Asseng et al., 2013; Müller, 2011; Rosenzweig et al., 2013).

~~Besides, there~~There is an increasing need ~~of better~~to improve understanding of the environmental and climate consequences of changes in cropland area and in management practices, 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~~ Many lines of evidence show that changes of cropland plant properties can strongly modify ~~strongly enough~~ the biophysical characteristics (albedo, roughness, turbulent fluxes) of the land surface, which affect~~ing~~ ~~in order to have an effect on~~ local and regional climates (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 has led to new model developments ~~to~~ that improve Land Surface Models (LSMs) ~~for including a~~so that they give a more realistic representation of crop processes (Bondeau et al., 2007; Gervois et al., 2004; Kucharik, 2003). The~~,~~ aim is~~ing~~ to simulate the spatial distribution and variability of crop production ~~as well as~~and ~~their~~ its water, energy, and carbon fluxes, all of which affect climate. These efforts have improved the seasonal dynamics of modeled foliar and biomass developments (Bondeau et al., 2007; Gervois et al., 2008; Gervois et al., 2004; 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~~ some 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 practices (Bondeau et al., 2007); and 3)~~.~~ ~~Incomplete~~ 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~~from the STICS agronomical model~~ — STICS~~, which has been extensively validated ~~as a generic crop model~~ and can~~to~~ simulate ~~various kinds of~~different crops (e.g., wheat, maize, soybean, bananas) (Brisson et al., 1998; Brisson et al., 2002)— into the carbon-water-energy LSM ORCHIDEE model (Krinner et al., 2005), resulting in~~to~~ a new~~n~~ Agro-Land Surface Model, ORCHIDEE-CROP (at version v0, hereafter referred to as ORCHIDEE-CROP, https://forge.ipsl.jussieu.fr/orchidee/wiki/DevelopmentActivities). ORCHIDEE-CROP ~~is developed for~~has ~~dual~~two applications:~~,~~ offline and online. Offline applications (presented here) ~~are useful~~improve ~~to~~ understanding of the mechanisms controlling yield, given climate and management forcing. Online simulations require the crop model to be coupled with an atmospheric model (GCM) when~~for~~ studying ~~feedbacks of~~ crop vegetation feedbacks on climate. ~~There exist s~~Several crop models have been developed for offline applications and impact studies, but very few of these models can be coupled with GCMs, e.g. because they do not represent albedo, roughness, and sensible and latent heat fluxes on the~~a~~ typical time step of ≈ 30 min, which are ~~needed fwhenor being~~ required to couple with~~d to~~ a GCM. Our efforts have focused on~~at~~ improving the representation of phenology,~~ and~~ the simulation of biophysical and biogeochemical fluxes, ~~as well as~~and on biomass and grain yields. ORCHIDEE-CROP can solve the incomplete coupling problems in the existing ORCHIDEE-STICS model (Gervois et al., 2004).

~~In the following, w~~We first describe the structure of ORCHIDEE-CROP (section 2) and evaluate the new model for phenology,~~ and~~ CO_2, and energy fluxes over winter wheat and maize sites across a large climate gradient in Europe~~,~~ using observations of biophysical and carbon variables (~~leaf area index [~~LAI~~]~~, biomass, latent (LE) and sensible heat (H) fluxes, and net ecosystem exchange~~s~~, NEE) from seven~~7~~ eddy covariance sites (section 3). Finally, we discuss the general performance of ORCHIDEE-CROP, ~~–and~~ its limitations ~~as well as~~and the future research that is needed (section 4).

2. Materials and methods

2.1 Model description

Two key processes of crop plants were introduced into a ~~crop specific~~ module integrated in ORCHIDEEv196 (version Tag196, http://forge.ipsl.jussieu.fr/orchidee/wiki/Tags/196, ~~we mention it as~~called ORCHIDEE hereafter). This module simulates ~~–~~crop phenology and the specific carbon allocation ~~of carbon~~ to grain ~~filling~~ prior to harvest (Fig. 1~~Fig. 1Fig. 1~~). This crop module is used to calculate 1) the seasonal dynamics of LAI, a key variable that impacts surface biophysical properties (albedo, roughness) and water, energy and carbon fluxes, and 2) the timing and amount of grain filling that determines yield.

In ORCHIDEE, the vegetation is ~~discretized~~ divided into 13 plant function types -(PFTs), including bare soil, 10 natural PFTs (e.g., evergreen and deciduous trees, C3, and C4 grass) and two crop PFTs (C3 and C4 crops) that are assumed to have the same phenology as~~than~~ natural grasslands, but with higher carboxylation rates (Krinner et al., 2005). More vegetation types can be simulated using a new PFT external definition module (http://labex.ipsl.fr/orchidee/index.php/about-orchidee). Several PFTs can coexist within the same grid cell (also 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~~entered into the atmospheric model, in order to avoid~~ease 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, which is the same as~~to~~ the processes in STICS ~~[~~(~~in detail see~~ Fig. 1 in Brisson et al., 1998). The timing and duration of each stage is calculated based on development units, which describe the~~ing~~ physiological requirements of crops. These development units are calculated,~~d 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 days. The vernalizing value of a given day (JVI) is a function of air temperature. The vernalization status

(RFVI) ~~for~~ of the vernalization sensitive crop increases gradually to ~~reach~~ one when the vernalization requirement is met (Supplementary Eqn. 1). The photoperiodic slowing effect, RFPI, is determined by two photoperiod thresholds, PHOBASE and PHOSAT, for photoperiodic crops. In the case of short-day crops, the PHOBASE is higher than PHOSAT, whereas in the case of long-day crops, the PHOBASE is lower than PHOSAT. The current photoperiod PHOI is calculated on the basis of calendar days and latitude (Sellers, 1965) (Supplementary Eqn. 2). Transition between stages occurs when the 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 stages makes it possible 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, and is 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~~and is dependent on soil dryness (Supplementary Eqn. 3). The growth rate of the epicotyl is assumed to be a logistic function that depends~~ing~~ on soil temperature and water status at the sowing depth (Supplementary Eqn. 4). Crop emergence occurs when the ~~elongation of~~ epicotyl elongates and is dependent on ~~>~~ planting depth (PROFSEM). The actual density of emerged plants is calculated from the initial sowing density, a fixed parameter, ~~considering the~~ which takes into account some 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). ~~At~~During this stage, ~~the~~ extremely cold temperatures can reduce the seedling density through its effects on both vernalization and thermal limits for cold-sensitive crops (e.g., winter wheat). 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 (Supplementary Eqn. 5) (Brisson et al., 1998). The leaf 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, leaf senescence ~~of LAI~~ is updated each day (Brisson et al., 2008). Extremely hot and/or cold temperatures ~~during~~from crop emergence to maturity can affect leaf dynamics through its effects on both the daily leaf growth increment and leaf senescence of crops, and thus ~~exert greatlarge~~significantly aeffects~~ on~~ ~~the consequent~~ photosynthesis and carbon allocations.

2.1.2 Photosynthesis, carbon allocation and yield

In ORCHIDEE-CROP, photosynthesis is calculated ~~with the equations of~~using ORCHIDEE (Krinner et al., 2005), which is 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 for~~of~~ CO_2 assimilation and the electron transport-limited rate for~~of~~ CO_2 assimilation, whose maximal values are the model parameters ~~(~~V_{cmax} and V_{jmax}, respectively~~)~~. These two parameters can be calibrated using, for instance, the 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.*~~–~~(Friedlingstein et al., 1999) and accounts for eight~~8~~ biomass compartments (leaves, roots, fruits/harvested organs, reserves, aboveground sapwood, belowground sapwood, aboveground heartwood, and belowground heartwood) for ~~natural~~ trees, and considers five~~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 for~~of~~ leaf and root biomass and grain yield (fruits/harvested organs), which are ~~described~~ driven by the phenology and LAI development parameterizations described in section 2.1.1. Specifically, the daily increment of leaf biomass for crops, Δ_{leaf_m}, is calculated by dividing the daily change ~~of~~ in LAI, Δ_{LAI}, by specific leaf area (*sla*), which is weighted by the water and nitrogen stress factors~~-~~ ~~weighted specific leaf area (*sla*)~~ (Brisson et al., 2008) as given by~~:~~

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

The daily increment for~~of~~ root biomass is determined by the daily total biomass increment and a daily 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 daily fraction of the ~~daily~~ increment for the~~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 the crop (when crop is harvested), and is restricted by an upper limit. The effects of extreme temperature~~ impact~~ on the grain filling process ~~and can stop carbon filling of harvested organs as~~are described ~~by~~ in the ~~(~~Supplementary Eq~~n.~~. 6~~)~~ (Brisson et al., 2008). The remaining daily net primary production~~ from ORCHIDEE~~ (NPP), once allocation ~~in~~to leaf, root, and grain biomass is performed (the latter occurring only after the start of the grain filling phase), ~~and~~ is allocated to the stem compartment to conserve mass. ~~In this case, t~~This “residual” stem ~~“residual”~~ compartment denotes ~~in fact~~ both the actual stem biomass and additional reserves. At harvest, a small part of the carbon (with the same amount allotted to planted seeds) is moved from harvested organs to the reserves pool. This mimics the amount of carbon that ~~for~~ seeds need~~ed~~ for the next crop season.

In ORCHIDEE-CROP, the ~~priority of~~ carbon allocation priority to different compartments was changed ~~to be~~so that it was consistent with the growth development phases derived from STICS. In the vegetative stages, the leaf and root have the highest priority. ~~In cases~~If the ~~net primary product (~~NPP~~)~~ supply cannot satisfy the leaf and root biomass demand, no carbon is allocated to stems and the required amount of carbon demanded 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 to~~of~~ the shoot/root ratio (~~yet~~ no carbon being allocated to the stem). However, in such extreme cases, the 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 the remaining NPP. If the NPP available after satisfying the grain demand ~~is satisfied~~ is not sufficient to ~~meet~~ support the allocation to the ~~grain~~leaf, then carbon is remobilized from stem and root according to a fixed shoot/root ratio. ~~(the reserve pool was used out before reproductive stages) according to a fixed shoot/root ratio.~~

2.1.3 Soil moisture limitation effect on plant growth

Water limitation for crop development and biomass production is accounted for through a water stress index calculated from ORCHIDEE, and ranges from~~ing in the interval [~~ 0 to ~~–~~1~~],].~~ ~~which is calculated from ORCHIDEE and applied to reduce~~It allows for reduced~~ing~~ leaf growth and accelerated~~inge~~ leaf senescence rates. The root water uptake function in ORCHIDEE is based on the assumption that the vertical root density ~~profile~~ distribution ~~is~~ exponentially decreases~~ing~~ with depth (Krinner et al., 2005) and that water uptake is a function of root zone extractible water weighted by ~~this~~ the root profile. Relative water content in the root zone is an index defined by the difference between actual water content and the wilting point, divided by the difference between field capacity and the wilting point. This index always varies between 0 and 1. Below a fixed relative root zone ~~integrated relative~~ water content threshold of 0.5, the ORCHIDEE stress index value decreases from 1 (no stress) to zero (wilting point). T~~,~~ ~~and t~~his~~e~~ stress index is used as a multiplier for~~of~~ both V_{cmax} and stomatal conductance, and ~~acting to~~leads to a decrease in ~~both~~ gross primary productivity and transpiration.

Two different soil hydrological schemes, namely a ~~[(the~~ two~~2~~ layer soil scheme, referred to as 2LAY ~~hereafter~~, and ~~the~~ an 11 layer soil diffusion scheme, referred to as 11LAY ~~(hereafter, in detail see (Guimberteau et al., 2014)]~~ (Guimberteau et al., 2014)~~)~~ ~~can be used alternatively in ORCHIDEE~~were used in this study to calculate soil moisture~~,~~ and all dependent ecosystem state variables. In ORCHIDEE-CROP (V0), ~~soil water dynamics between~~soil hydrology is simulated for three separate soil tiles in each grid cell. These three tiles are covered by bare soil, short vegetation (including crops), and by forest vegetation~~, respectively~~. Here, for site-scale simulations, we assumed a grid cell with single tile entirely covered by crops.

~~different soil layers for all PFTs within a vegetation mosaic share the same hydrological framework in SECHIBA module but with different parameterizations for different PFTs.~~

Relative root extractible soil moisture in the different soil layers ~~is~~ was computed ~~by~~ in 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 was~~is~~ then calculated based on relative root extractible water, which differs between the 2LAY and the 11LAY versions. ~~Application of water~~ ~~i~~Irrigat~~ed~~ion was~~is~~ not taken into account in the current version of ORCHIDEE-CROP

~~and. wWe keep the default hydrological framework for both natural and crop PFTs as developed in ORCHIDEE (also see the discussion section).~~ The typical exponential (~~and~~ static) root profile assumed for grass and crop PFT in ORCHIDEE ~~assumes that~~locates ~65% of the roots ~~are above~~in the upper 20 cm of the soil. This root distribution profile was~~is~~ different from the one that was used in STICS, where ~~only~~ fewer roots were assumed to be in the upper 20 cm of soil and more below (Brisson et al., 2008; Gervois et al., 2004). ~~But i~~In ORCHIDEE-CROP we kept~~ep~~ the root profile as parameterized in ORCHIDEE.

2.1.4 Simplified nitrogen limitation and fertilization effects

Nitrogen fertilization ~~allows to~~ increases crop productivity and the LAI, which consequently impacts on 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) and expressed it 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 introduced an additive nitrogen response parameter, N_{add}, which is ~~of~~ linked to photosynthetic parameters, V_{cmax_opt} and $J_{\max\_opt}$, using the following equation:

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

w~~W~~here N_{max} is the maximum additive effects of nitrogen fertilization during the growing season, N_{fert}, on the photosyn~~s~~thetic parameters (for~~in~~ details see Chang et al., 2015). The N_{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 allowed~~s~~ us to estimate the 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 using~~for~~ winter wheat and maize at seven~~7~~ eddy-covariance sites, which are part of~~ of~~ the CarboEurope-IP project (http://www.carboeurope.org/). The~~os~~e sites span different climatic conditions (Table 1 and Fig S1). All the sites recorded the meteorological half-hourly variables necessary to run ORCHIDEE-CROP as well as CO_2 fluxes (NEE), and ~~and~~ latent and sensible heat fluxes. The NEE half-hourly data were gap-filled and partitioned into gross primary productivity (GPP) and total ecosystem respiration (TER) using the online eddy covariance processing tool (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 for~~at~~ each site and were used either for parametrization (sowing date, fertilization) or evaluation purposes. The geographic locations, climate regimes, and management information~~s~~ are provided in Table 1,

Table 2, and Fig. S1. More details about the seven~~7~~ sites can be found in (Kutsch et al., 2010; Vitale et al., 2007).

2.2.2 Climate forcing data and atmospheric CO$_2$

At each site, meteorological forcing ~~measured on the top of each flux tower~~ on a half-hour time step~~,~~ was ~~directly~~ used as a model input.~~,~~ This included~~ing~~ air temperature, precipitation, wind speed, atmospheric water vapor pressure, shortwave and longwave incoming radiation, and ~~long-wave incoming radiation,~~ mean near-surface atmospheric pressure. Annual CO$_2$ atmospheric concentration ~~is~~ was ~~prescribed~~ derived from background atmospheric measurements. ~~Because of~~There were gaps in the meteorological data, mainly caused ~~mainly~~ by instrumentation malfunction. Therefore,~~,~~ we reprocessed ~~them~~ the data using standardized procedures for~~of~~ gap-filling and quality control (Moffat et al., 2007; Papale, 2006). A significant source of systematic errors ~~when~~ in comparisons~~ing~~ between modeled and eddy covariance ~~observed~~ fluxes ~~is~~ were attributed to the lack of energy balance closure in the eddy covariance ~~using eddy covariance data~~measurements (Foken, 2008). Our evaluation revealed an obvious problem regarding the energy balance closure in the eddy covariance observations on these crop sites~~,~~ where~~ith~~ the energy closure rate ranged~~ing~~ from ~ ~~∼~~80.6% to ~~∼~~86.3% (e.g., Fig. S2). We thus ~~performed corrections of~~corrected the daily LE and H measurements in a similar way to Twine *et al.* (Twine et al., 2000) and Jung *et al.* (Jung et al., 2011), which preserved the Bowen ratio:

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

where, E is either the LE or H flux, α is a daily correction factor, and R_n and G ~~is~~ are the net radiation and ~~ground~~ soil heat ~~storage~~flux, respectively. In our correction, we do not consider the ~~ground~~ soil heat ~~storage~~ flux due to the lack of observations. Although the magnitude and causes of energy ~~balance~~ budget imbalance ~~likely~~ probably vary among sites and across time scales ~~(Barr et al., 2006; Franssen et al., 2010),~~ (Barr et al., 2006; Franssen et al., 2010),~~.~~ t~~this T~~his simplified approach can correct the energy balance closure gap and yields 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-CROP to evaluate the performance of ORCHIDEE-CROP and the impacts of the parameterizations of the nitrogen limitation factor and soil hydrology schemes~~, 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~~ described by the C3 crop ~~stantard~~ standard parameters and maize by the standard C4 crop ones). The same mean soil depth and soil water holding capacity were prescribed for the seven~~7~~ sites, and were 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~~For each site, we selected one year of observation during which winter wheat or maize was cultivated. The sowing date was ~~prescribed to~~inputted into the model for each crop-site according to the management data (Table 2~~),~~). However,~~but~~ the harvest date in ORCHIDEE-CROP was ~~caculated by the model~~determined by crop development processes. The observed nitrogen fertilization and irrigation information for each crop-site were used in STICS experiment STI-WN (Table 2 and Table 3). In STICS, the real date and quantity of applied irrigation and nitrogen fertilization can be introduced into the model, which~~- and~~ ~~are involved~~affects ~~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~~ where the climate was obtained ~~with~~ using a model spin-up. For this spin-up, site-specific meteorological ~~½~~ half-hourly data was repeatedly cycled for 300 years to force ORCHIDEE and ORCHIDEE-CROP until the soil water reached a steady state (data not shown). Then, simulations were conducted for the period of evaluation, starting ~~with starting~~ from the initial conditions at the end of model spin-up. Notably, C input from manure ~~input~~ applications was~~is~~ not taken into account in this study~~,~~ due to a lack of data for historical manure applications.

The same cultivar choice (represented by the ~~parameters of~~ “Soissons” and “DK250” variety~~ies~~ parameters in STICS for winter wheat and maize, respectively), rather than site-year specific varieties~~ choice~~, ~~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 was~~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~~budgets. The experimental ~~detailed ensemble of~~details ~~– experiments~~ are~~is~~ shown in Table 3.

2.3 Metrics for evaluating model performance

Three metrics were used to evaluate the model-data agreements~~. These were with available observations~~ at a daily resolution for ~~different fluxes (~~NEE, H, and LE fluxes,~~)~~ and ~~f~~the~~or~~ 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

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

where P_i is the modelled data, O_i is the observed data, $\bar{O}$ is the observed mean and n is the numbers 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~~ all sites. This metric~~s~~ estimates the proportion of total variance in the observed data that can be explained by model, and is given by

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

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, expressed as~~:~~

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

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

where ~~P_i~~ and ~~O_i~~ ~~is modelled and observed data, respectively, and n is the number of data.~~ $Omax$ and $Omin$ are observed maximum and minimum data.

3. Results

3.1 Crop phenology, plant development stages and productivity

Comparison of the seasonal evolution of observed and modelled LAI for winter wheat and maize at different sites ~~is iswasis~~was shown in Fig. 2~~Fig. 2Fig. 2~~. The modelled seasonality for~~of~~ LAI ~~wasis~~has been markedly improved by ORCHIDEE-CROP (ORC-CP1, Table 3) compared ~~with~~ to ORCHIDEE, for both winter wheat and maize. The correlation coefficient between observed daily LAI and modelled daily LAI ~~showed a marked~~n ~~($p < 0.05$)~~ increasedd~~e~~ from ~~ORCHIDEE to ORCHIDEE-CROP (ORC-CP1) from~~ 0.44 ±0.22 to 0.83 ±0.17 for winter wheat and from 0.64 ±0.22 to~~vs~~ 0.79 ±0.10 for maize ~~using~~from ORCHIDEE ~~and~~to ORCHIDEE-CROP (ORC-CP1), respectively. The IOA increase~~s~~d from 0.47 ±0.11 to 0.82 ±0.12 (winter wheat) and from 0.57 ±

0.15 to 0.85 ± 0.08 (maize), with a significant decrease in~~of~~ RMSE (2.71 ± 0.49 vs. 1.12 ± 0.36 and 2.06 ± 0.86 vs.~~.~~ 1.04 ± 0.31 for winter wheat and maize, respectively) (Fig. 2~~Fig. 2Fig. 2~~, Table 4, Figs. 5a~~–~~b). Despite its overall good performance for LAI, ORC-CP1 (under moderate nitrogen limitation ~~to~~ of leaf growth) could ~~can~~not reproduce ~~the amplitude of~~ the observed LAI within the measurement uncertainty (personal communications with PIs in 2014) at a few sites (Fig. 2~~Fig. 2Fig. 2~~). For example, maximum LAI was~~is~~ underestimated by 49% and 28% for winter wheat at~~in~~ FR-Gri and FR-Lam, respectively. Reducing the nitrogen limitation ~~for~~ of leaf growth (ORC-CP3) at these two sites could~~can~~ improve the modelled maximum LAI and bring it into 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 was~~is~~ in good agreement with the observations (~~with~~ IOA = 0.96 and RMSE = 25.4 days) (Fig. 3~~Fig. 3Fig. 3~~).

~~Along with the an~~The accurately simulated timing and amplitude of LAI improved ~~,~~the seasonal evolution of aboveground biomass (AGB) ~~was gotets improved~~ in ORCHIDEE-CROP (ORC-CP1) compared ~~with~~ to ORCHIDEE for both winter wheat and maize, except at BE-Lon for winter wheat and at NL-Lan for maize (Fig. 4, Fig. 5~~Fig. 5Fig. 5~~). In general, the bias of the modelled AGB was~~is~~ attributable to the bias in the~~of~~ modelled LAI~~,~~ as indicated by the ~~a~~ significant ($p < 0.005$) relationship between ~~them~~ AGB and LAI 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 was~~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 ~~was underestimated (e.g., winter wheat at FR-Gri and FR-Lam) (Fig. 2, Fig. 4, Fig. S5). ~~In the~~The ~~reality~~observation data did not show a~~,~~ ~~the ~~decrease in above-ground biomass ~~does did not start ~~until harvest (Fig. 4~~Fig. 4Fig. 4~~).

ORCHIDEE-CROP (ORC-CP1) could~~an~~ capture the timing of grain filling and yield harvest well compared~~ing~~ 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 showed that there was ~~around ~~a ~~~~~19~~% ~~% to 30% underestimation of crop yields in ORC-CP1 without fertilization (Fig. 6~~Fig. 6Fig. 6~~), compared~~ing~~ to a good match (NRMSE ~~~~~= ~8.8%) between STICS with real fertilization (STI-WN) and the observed data~~ations~~ (Fig. S6). However ORCHIDEE-CROP with real fertilization (ORC-CP4) ~~can ~~could produce a better estimation of crop yields for these two sites than ORCHIDEE-CROP without fertilization (ORC-CP1), leading to a ~~~~~50% reduction in the NRMSE (47% vs. 23% for ORC-CP1 ~~and ~~vs. ORC-CP4, respectively) (Fig. 6). Considering the measurement uncertainties of FR-Aur and FR-Lam for crop yields (personal communications with PIs in 2014), ORCHIDEE-CROP, with ~~the ~~its simple nitrogen fertilization~~,~~ parameterization, ~~on crop productivity ~~generally ~~conserves conserved~~showed reasonable performance compared to STICS, ~~that ~~ ~~because it~~which ~~has hasd~~ a ~~full-fledge~~complete nitrogen cycle~~, thatto~~ and captures both the timing and amplitude of crop yields.

3.2 CO$_2$ and energy fluxes

ORCHIDEE-CROP had~~s~~ a more realistic simulated seasonality and amplitude for~~of~~ NEE at most of the winter wheat sites than ORCHIDEE (significant increase in~~of~~ IOA and *r* and decrease in~~of~~ RMSE from 2.9 ±0.2 g C m^{-2} day^{-1} ~~of~~ in ORCHIDEE to 1.9 ±0.5 g C m^{-2} day^{-1} ~~of~~ in ORC-CP1). Improved performances of ORCHIDEE-CROP over ORCHIDEE were also found ~~and~~ at the maize sites in humid regions (Fig. S1, Fig. 7~~Fig. 7Fig. 7~~). Along with leaf area development ~~(LAI)~~ during the growing season,~~;~~ the model ~~produces~~ produced a CO$_2$ sink until shortly before harvest, when most leaves ~~are~~ were senescent and crop photosynthesis ~~cannot~~ could not compensate for respiration, which ~~is~~ was consistent with the~~to~~ observed data~~ations~~ (Fig. 7~~Fig. 7Fig. 7~~). ORCHIDEE-CROP ~~can~~ could also capture the observed peak in~~of~~ CO$_2$ release to atmosphere shortly (ranging from 10 to -20 days, Fig. 7) after harvest for both winter wheat and maize, which was mainly due to ~~mainly~~ increased~~to the pulse of~~ litter decomposition.

However, there ~~is~~ was a mismatch between the simulations and observations regarding the temporal evolution~~s~~ of NEE for winter wheat in BE-Lon, ~~with a~~where there was a weaker and earlier termination of CO$_2$ uptake in the model (Fig. 7~~Fig. 7Fig. 7~~). The underestimated LAI and earlier cessation of crop growth in ORC-CP1 at this site resulted in~~to~~ a negative bias ~~of~~ for GPP during the late growing season (~170 days after sowing) (Fig. 2~~Fig. 2Fig. 2~~, Fig. S7), which ~~contributes~~ contributed to the underestimation of NEE uptake ~~during the same period~~ (Fig. 7~~Fig. 7Fig. 7~~, Fig. S8). Notably, ORC-CP1 ~~overestimates~~ overestimated the NEE peak uptake of CO_2 for maize at sites with drier climates ~~regimes~~ in Europe (e.g., FR-Lam and IT-Bci). The overestimation of NEE at these summer-dry sites ~~is~~ was probably~~ mainly~~ (~~∼~~68%–~~-~~85% of explained variance ~~as~~ revealed by the~~a~~ G~~g~~eneral~~ized~~ L~~l~~inear M~~m~~odel) caused by ~~the~~ an overestimation of GPP rather than by an underestimation of ecosystem respiration in ORC-CP1 (Fig. S7, Fig. S8). Further analysis ~~shows~~ showed a much higher ($p < 0.05$) rate for~~of~~ GPP per unit LAI in ORC-CP1 than observ~~ations~~ed~~ed~~ at the~~se~~ southern ~~European~~ maize sites (Fig. S9). Notably, ~~the~~ ORCHIDEE-CROP with the 11-LAY hydrological scheme (ORC-CP5) ~~improves~~ improved the modelled NEE ~~largely~~ for maize at these sites~~, with a~~because it showed a ~~∼~~40% decrease in the NRMSE (Fig. 7).

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

Consistent with the overestimation of H in ORC-CP1, ~~ORC~~LE was ~~-CP1~~ generally ~~underestimates~~ underestimated ~~LE among~~at the wheat sites (Fig. 9). A more realistic estimation of LE was ~~observed~~ obtained by~~in~~ ORC-CP5 for a majority of the ~~crop-~~ sites ~~simulations than ORC-CP1~~, showing a ~~\~~~32% decrease in NRMSE from ORC-CP1 to ORC-CP5.~~,~~ The e~~E~~exceptions were~~are~~ the winter wheat and maize simulation ~~on~~ at the DE-Kli site, which could be attributed to a considerable energy balance gap (with an energy closure of ~73%) ~~in~~at this site (Fig. 9). For ~~the~~ maize, ~~– simulation at DE-Kli,~~ ORC-CP5~~,~~ ~~overestimates~~ overestimated ~~the~~ LE at DE-Kli~~,~~ ~~for~~ by ~~~\~~~110% compared to ~~with~~ the observed data.~~ations.~~ The LE values were also overestimated ~~At this site, was, while ORC-CP5 also overestimates overestimated the LE~~ for wheat ~~at DE-Kli~~ during the early- and mid-~~-~~growing season (from sowing to 230 days ~~since~~ after sowing). The overestimation of LE at DE-Kli ~~this site for both winter wheat and maize is~~ was ~~not neither likely to~~not ~~– raise be~~ explained ~~from~~ by the ~~the simulated a bias of~~ LAI bias (~~good estimation,~~ see above) nor ~~from~~ by ~~the~~ a systematic error in LE due to the effects of rainfall events (with daily rainfall ⩾ 3 mm) (Figs. 8–~~-~~9), but was possibly due to 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 ~~(~16% of RMSE) ~~bias ~~of ~~in LE simulated ~~in ~~by ORC-CP5 at the wheat site FR-Lam during the peak leaf growth (~~during ~~210–~~-~~250 days after planting) ~~is ~~was due to an underestimation of the LAI (Fig. 9, Fig. 2). The slight overestimation of~~-~~ LAI for maize during periods of peak leaf growth (e.g., FR-Lam and NL-Lan) ~~does ~~did not ~~appear however to ~~translate~~s~~ into a related overestimation of LE. This ~~illustrates~~ illustrated the divergent responses of LE to changes ~~of ~~in LAI between ORCHIDEE-CROP and the observations, which ~~can ~~could be due to several factors,~~;~~ such as the parameterization of soil water stress (Fig. S11). The episodes of LE with low biases (during LE peaks~~ of LE~~) ~~are were symmetrical to episodes of~~coincided with high H biases, even though net radiation appeared~~s~~ to be realistic, except for the maize site IT-Bci in Italy (Fig. S12).

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

4. Discussion

4.1 General performance of ORCHIDEE-CROP

~~The~~ ORCHIDEE-CROP has been~~is~~ developed ~~here~~ as an Agro-LSM ~~by adopting~~and adopts a generic framework ~~through~~to integrate~~ing~~ the crop processes from~~of~~ STICS into the ~~DGVM model~~ ORCHIDEE LSM.~~. Managed and natural vegetation share the same fundamental biophysical and biochemical functions within the DGVM framework~~. Given its generic structure, ORCHIDEE-CROP, tested ~~in this study for~~using wheat and maize in this study, can simulate ~~many different kinds of~~other crop types~~s over the global with a generic crop development structure~~. ~~The~~ C~~c~~rop phenology, development~~s~~, carbon allocation~~s~~ and ~~crop~~ grain filling ~~are with a relatively complete scope and simulated explicitly driven by~~can be calculated from climate ~~conditions~~forcing data~~,include~~ and is mediated by limiting factors (e.g., nitrogen, extreme temperatures,~~,~~ and low soil moisture).

~~Marked~~ A significant improvement ~~is~~ was ~~achieved~~ obtained ~~by~~ using~~in~~ ORCHIDEE-CROP compared~~ing~~ ~~with~~ to ORCHIDEE for the simulated ~~timing and amplitudes of plant developments (~~crop phenology and development~~)~~ ~~for winter wheat and maize~~ at different winter wheat and maize sites~~sites investigated in Europe,~~. It showed ~~showing agreements with observations within~~ 65%–~~-~~95% (IOA) for biometric data and 78%–~~-~~98% (IOA) agreement with the observed data for all turbulent fluxes, despite the lack of detailed crop management (e.g., irrigation, fertilization) parameterization (Figs. 2–~~-~~9)~~,~~ and the lack of an explicit calculation for the~~of~~ nitrogen cycle in the croplands.

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

Improvements in~~of~~ crop phenology and carbon allocation le~~a~~d to a general good match of the seasonality between modelled and observed AGB (with NRMSEs of 11%–~~-~~54%), crop yields, and~~,~~ ~~as well as ~~carbon and energy fluxes (NRMSEs 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 revealed that the 11LAY hydrological scheme can improve the modelling of soil water dynamics and hence lead to a better simulation of leaf growth and ~~the ~~consequent~~ly~~ biochemical and biophysical variables, especially for the C4 crops planted in the drier climate zones of Europe (Fig. 7–~~-~~9~~),~~). ~~which ~~This in turn exerts great effects on the estimations of carbon balances in these regions, especially in the 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 ~~distribution of active roots, which is considered as fixed in all ~~the versions of ~~ORCHIDEE versions. ~~Such~~The use of a static root profile is one limit on the~~ation to~~ calculation of~~e~~ water stress, but the use of ~~a ~~11-Layer hydrology allows ~~to ~~us to simulate shifts in root uptake from the surface to deeper horizons as the soil dries out during drought. ~~distribution scheme in ORCHIDEE-CROP could undoubtedly add some bias in the simulation of crop growth, water and energy (e.g., the latent heat) fluxes. ~~An important ~~direction task for future improvement~~ area for further research ~~would~~ could 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~~ which showed a ~~~~~50% decrease in the NRMSE (Fig. 6). The remaining discrepancies in~~of~~ simulated crop yields~~,~~ and energy fluxes are generally within the observed uncertainties for~~of~~ measurement and energy balance closure. More importantly, ORCHIDEE-CROP has ~~good~~ the ability to capture the spatial gradients of crop-related flux~~es~~ variables, such as GPP, NEE, H, and LE,~~,~~ across the studied sites in the different European climate zones ~~of Europe~~ (Fig. 10, Figs. S14–~~-~~S16). This is important for further applications of this model using gridded data over Europe, or even the globe, ~~to~~ when attempting to investigate regional/global yield variations~~,~~ and the interactions between croplands and the climate system. C~~, while the c~~roplands ~~has~~ have ~~the~~ potentially crucial climate feedbacks ~~from~~ regarding the ~~increasing~~ increased intensification of agricultural activities and ~~as well as~~ land use 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 the simplified representation of nitrogen limitation on crop growth and fertilization effects (~~in detail see~~ section 2). Alleviation of nitrogen limitation on leaf growth ~~on~~ at ~~these~~ those sites can improve the simulated amplitudes of LAI and capture the maximum LAI (Fig. S3). ~~Actually, n~~Nitrogen limitation has a strong influence on the seasonal evolution~~s~~ of crop growth (Fig. S3~~), ~~). ~~and a~~A more realistic representation of intra-seasonal nitrogen processes (results based on STICS with an explicit nitrogen cycle) leads to a generally much better match between the modelled and observed LAI, except for ~~the ~~NL-Lan ~~for~~ and maize (Fig. S13).

~~Lack of~~The failure to modell~~ling~~ ~~of the ~~irrigation effects~~s~~ ~~–~~can also ~~contribute ~~introduce some bias to the simulated LAI and other variables. Soil water stress on GPP and LE, which also ~~impacting~~affects carbon allocation~~ as well~~, plays an important role in controlling crop development~~s~~, especially for summer crops (e.g., maize) planted in regions with dry summer episodes (Fig. S1, Table 1~~), ~~). ~~where ~~Those regions are currently suffering from intensive irrigation management~~s~~ ~~currently ~~(Table 2) and ~~possibly ~~there will possibly be an increase ~~of ~~in irrigation requirements as the climate warms~~along with the climate warming~~ (Döll, 2002). As illustrated by our results ~~that~~ the lack~~ing~~ of irrigation management~~s~~ in the current version of ORCHIEE-CROP leads to a lower LAIs in the later crop season at FR-Lam for maize in drier climate zones (Fig. 2 and Fig. 7),~~,~~ which, in turn, affect NEE and the energy budget (Fig. 7–~~-~~9). More importantly, the projected increased~~ing~~ drought stress for ~~current ~~cultivated croplands (Dai, 2012),~~,~~ with a more intense and longer lasting droughts 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

I~~The i~~rrigation (as discussed above) effects~~s~~ on the crop development~~s~~ and yields are not accounted for in ~~this study~~the current version of ORCHIDEE-CROP,~~,~~ ~~and it is yet~~but it is important ~~for~~ when attempting to investigate~~ing~~ the historically long-term changes in~~of~~ crop yields ~~during~~ over recent~~ly~~ ~~past~~ decades, as ~~the~~ intensive human management has tended to ~~s~~ occur ~~mainly~~ since approximately the middle of the 20th century.

Several studies have shown that the spatial differences in crop management~~s~~ contribute significantly to the tempo-spatial patterns of crop yields (Licker et al., 2010; Lobell and Field, 2007), ~~besides~~ as well as the impacts of climate and soil fertility (Rosenzweig et al., 2013). Adaptive improvements in agricultural management~~s~~ are regarded as a potential way to close the "*yield gaps*" in a relatively sustainable manner ~~for social environmental system~~ (Licker et al., 2010). How the model handles human management factors (e.g., irrigation and fertilization) and their interactions with changing CO$_2$ and climate variations could have significant impacts on the ~~simulations of~~ crop ~~evolutions and~~ production simulations~~s~~ and the consequent land surface carbon budgets (Prescher et al., 2010). Additionally, our current crop development module embodies a number of simplifications for ~~the~~ pests, diseases, and weeds, which ~~are~~ we assumed to be controlled. ~~Besides, the e~~Extreme soil conditions (e.g., high salinity or acidity) are also crudely assumed to ~~exert~~ have little effect~~s~~ on crop growth. T~~All t~~hese factors can also introduce great uncertainties into the biophysical and biochemical simulations ~~over~~ of croplands.

Therefore, explicit nutrition dynamics and a human management (e.g., irrigation, fertilization, ~~application~~ introduction of new crop varieties, and pest management, etc.) module ~~are with primary priority~~need to be included in the updated version of 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 program, 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 the~~a~~ generally good performance of ORCHIDEE-CROP at predicting~~in~~ crop phenology, productivity, ~~as well as~~and the biosphere-atmosphere carbon and energy exchanges in pan-Europe temperate crop sites covering different climate zones, even without the explicit human management module. It b~~B~~enefits~~ing~~ from ~~the~~ a generic strategy in the crop module, which makes ORCHIDEE-CROP ~~can be~~ widely applicable at the regional and global scale. Explicit parameterizations of crop development processes in ORCHIDEE-CROP can improve the simulations of both the seasonality and magnitudes of LAI for croplands, which in turn ~~affects~~affect the consequent surface roughness, surface albedo, water, energy, and carbon budgets for land surfaces. Therefore, ~~Moreover, w~~with respect to future climate change, ORCHIDEE-CROP will allow us~~ not only~~ to predict the footprints of climate variations ~~in ~~on food security, ~~but also to~~and to simultaneously account for feedbacks caused by~~of~~ changes in crop behaviors to the atmosphere by coupling it to a general atmospheric circulation model (e.g., LMDz).

Nevertheless, ~~a ~~further improvement, especially ~~the ~~with regards to explicit nutritional dynamics and human management, is ~~with ~~a primary priority and could significantly improve our ability to understand and predict the role of croplands in the biosphere-atmosphere continuum, in the 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).

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7. 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 Xiuchen Wu (xiuchen.wu@bnu.edu.cn) or Nicolas Vuichard (nicolas.vuichard@lsce.ipsl.fr).

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Tables

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

Crop type	SiteID	Country	MAP [*]	MAT [†]	Longitude	Latitude	Altitude (m)	KGCC [ǂ]
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
	Be-Lon	Belgium	800	10	4.74	50.55	165	Cfb
Maize	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:
* MAP: mean annual precipitation;
† MAT: mean annual temperature;
ǂ KGCC, the Koppen-Geiger climate classifications.

Table 2. Management information for different crop-sites.

Crop type	SiteID	Year (sowing)	Sowing date	Irrigation (mm)					Fertilization (Kg N/ha)			
Winter wheat	FR-Lam	2006	291	0	0	0	0	0	46.5 (8 Jan 2007)	48.2 (4 May 2007)	\	\
	FR-Gri	2005	301	0	0	0	0	0	55.0 (15 Mar 2006)	55.0 (14 Apr 2006)	\	\
	FR-Aur	2005	300	0	0	0	0	0	50.0 (25 Jan 2006)	40.0 (23 Mar 2006)	33.5 (12 Apr 2006)	\
	DE-Kli	2006	269	0	0	0	0	0	74.3 (8 Apr 2007)	53.8 (4 May 2007)	35.8 (4 Jun 2007)	43.1 (22 Jun 2007)
	Be-Lon	2006	286	0	0	0	0	0	40.0 (17 Mar 2007)	60.0 (12 Apr 2007)	94.5 (8 May 2007)	\
Maize	FR-Lam	2006	121	25.0 (13 Jun 2006)	33.0 (3 Jul 2006)	27.8 (15 Jul 2006)	18.0 (26 Jul 2006)	44.0 (10 Aug 2006)	91.0 (8 Jun 2006)	\	\	\
	FR-Gri	2005	129	0	0	0	0\	0	140.0 (9 May 2005)	\	\	\
	DE-Kli	2007	118	0	0	0	0	0	17.3 (22 Apr 2007))	67.2 (13 Jun 2007)	\	\
	NL-Lan*	2005	138	0	0	0	0	0	\	\	\	\
	IT-Bci	2004	129	21.8 (24 Jun 2004) 22.1 (27 Jul 2004)	27.2 (2 Jul 2004) 19.3 (31 Jul 2004)	20.3(15 Jul 2004) 22.9 (5 Aug 2004)	25.7 (18 Jul 2004) 22.1 (12 Aug 2004)	23.4 (20 Jul 2004) 15.0 (21 Aug 2004)	22.5 (8 May 2004)	142.0 (11 Jun 2004)	\	\

Note: * There is strong organic fertilization. \ indicates no fertilization records.

Table 3. Description of the ensemble of simulations.

Name of experiments	Description of experiments	Irrigation	Nitrogen processes [*]	Soil water scheme [ǂ]	Stlevdrp (GDD) [¶]	Stdrpmat (GDD) [‼]
STI-NN	STICS without fertilization during crop development [‖]	NO	DY	\	540/990	750/600
STI-WN	STICS with actual fertilization based on management records [¦]	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:

[*] 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.

[ǂ] 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.

[¶] The accumulated growing degree days (GDD) from crop emergence to start of grain filling for winter wheat (C3 crop) and grain (C4 crop), respectively.

[‼] The accumulated growing degree days (GDD) from start of grain filling to crop mature for winter wheat (C3 crop) and grain (C4 crop), respectively.

[‖] JavaStics (v11.0) used here was obtained from http://www6.paca.inra.fr/stics.

! The detailed crop managements for each crop-site were shown in Table 2.

Table 4. Comparisons between observations and different simulations.

Crops	SiteID	IOA				R				RMSE (m^2 m^{-2})				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**	0.98***	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*	0.83**	0.86**	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**	0.92*	0.97**	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**	0.91*	0.89*	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*	0.74	0.89*	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*	0.76*	0.88*	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**	0.92**	0.97***	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*	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*	0.84*	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.

*, ** and *** indicates statistically significant at 5%, 1% and 1‰ level, respectively.

Figure captions

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.

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.

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.

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.

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 $m^2\ m^{-2}$ and $g\ C\ m^{-2}$, 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).

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 (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.

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 $\geqslant$ 3 mm) during the modelled growing season. The upper and lower panel shows the results for different sites of winter wheat and maize, respectively.

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

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.

Figures

Fig. 1

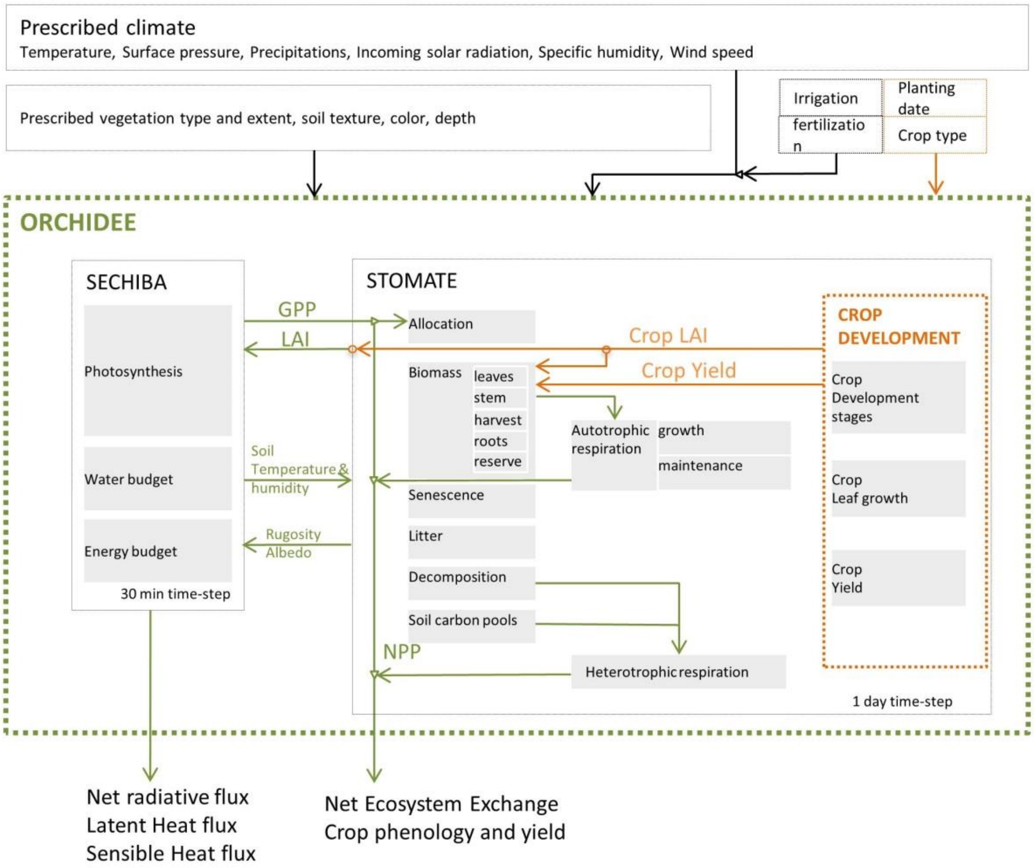


Fig. 2

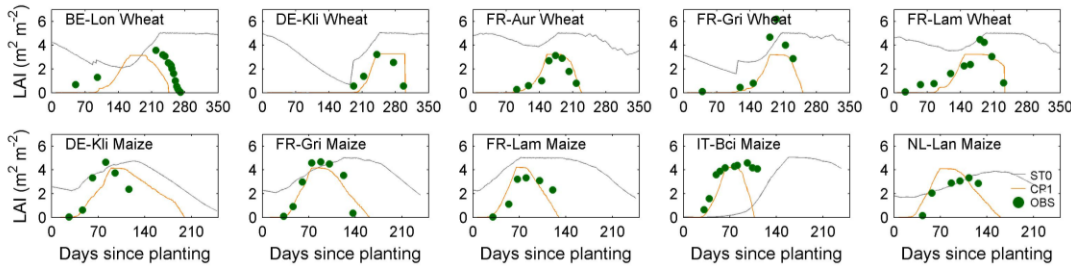

BE-Lon Wheat
DE-Kli Wheat
FR-Aur Wheat
FR-Gri Wheat
FR-Lam Wheat
DE-Kli Maize
FR-Gri Maize
FR-Lam Maize
IT-Bci Maize
NL-Lan Maize
LAI (m^2 m^{-2})
0
2
4
6
0
70
140
210
280
350
Days since planting
ST0
CP1
OBS

Fig. 3

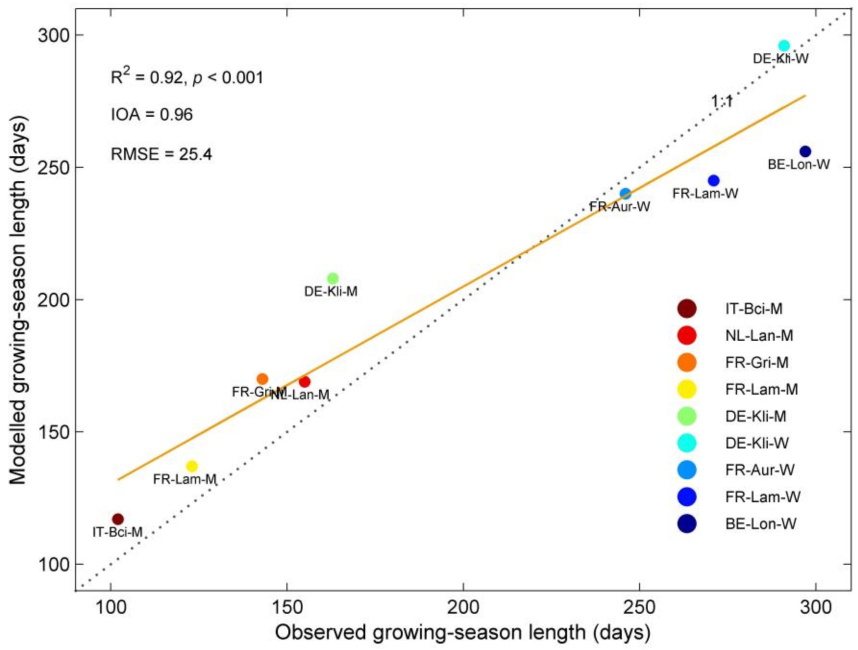

R^2 = 0.92, p < 0.001
IOA = 0.96
RMSE = 25.4
1:1
DE-Kli-W
BE-Lon-W
FR-Lam-W
FR-Aur-W
DE-Kli-M
FR-Gri-M
NL-Lan-M
FR-Lam-M
IT-Bci-M
IT-Bci-M
NL-Lan-M
FR-Gri-M
FR-Lam-M
DE-Kli-M
DE-Kli-W
FR-Aur-W
FR-Lam-W
BE-Lon-W
Modelled growing-season length (days)
Observed growing-season length (days)
100
150
200
250
300
100
150
200
250
300

Fig. 4

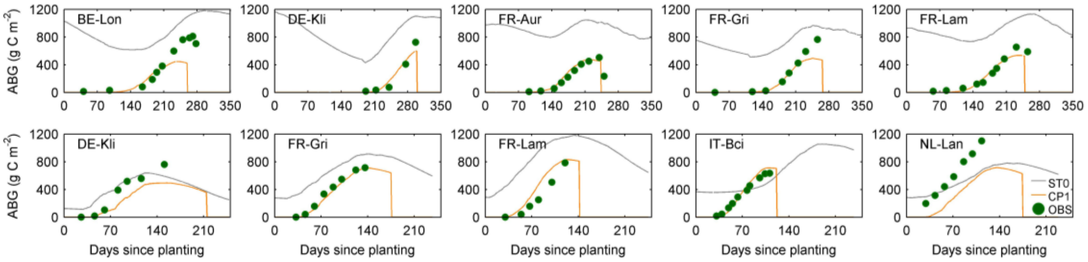

BE-Lon
DE-Kli
FR-Aur
FR-Gri
FR-Lam
DE-Kli
FR-Gri
FR-Lam
IT-Bci
NL-Lan
ABG (g C m^{-2})
0
400
800
1200
0
70
140
210
280
350
Days since planting
ST0
CP1
OBS

Fig. 5

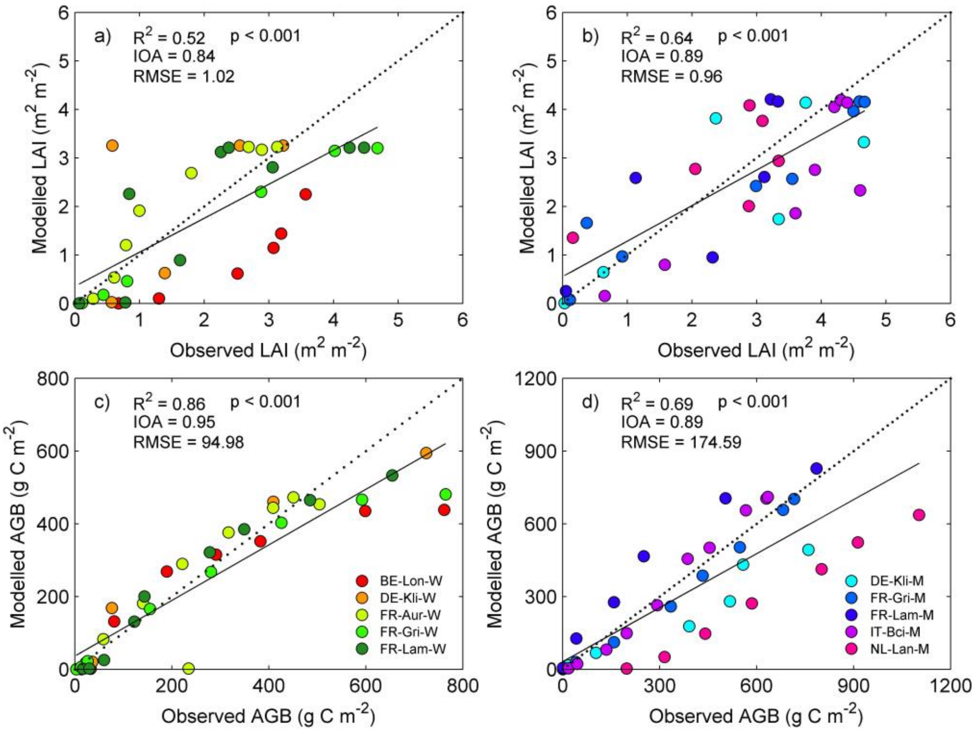

a)
$R^2 = 0.52$ $p < 0.001$
IOA = 0.84
RMSE = 1.02
Modelled LAI (m^2 m^{-2})
Observed LAI (m^2 m^{-2})
0
1
2
3
4
5
6
b)
$R^2 = 0.64$ $p < 0.001$
IOA = 0.89
RMSE = 0.96
Modelled LAI (m^2 m^{-2})
Observed LAI (m^2 m^{-2})
c)
$R^2 = 0.86$ $p < 0.001$
IOA = 0.95
RMSE = 94.98
Modelled AGB (g C m^{-2})
Observed AGB (g C m^{-2})
0
200
400
600
800
BE-Lon-W
DE-Kli-W
FR-Aur-W
FR-Gri-W
FR-Lam-W
d)
$R^2 = 0.69$ $p < 0.001$
IOA = 0.89
RMSE = 174.59
Modelled AGB (g C m^{-2})
Observed AGB (g C m^{-2})
0
300
600
900
1200
DE-Kli-M
FR-Gri-M
FR-Lam-M
IT-Bci-M
NL-Lan-M

Fig. 6

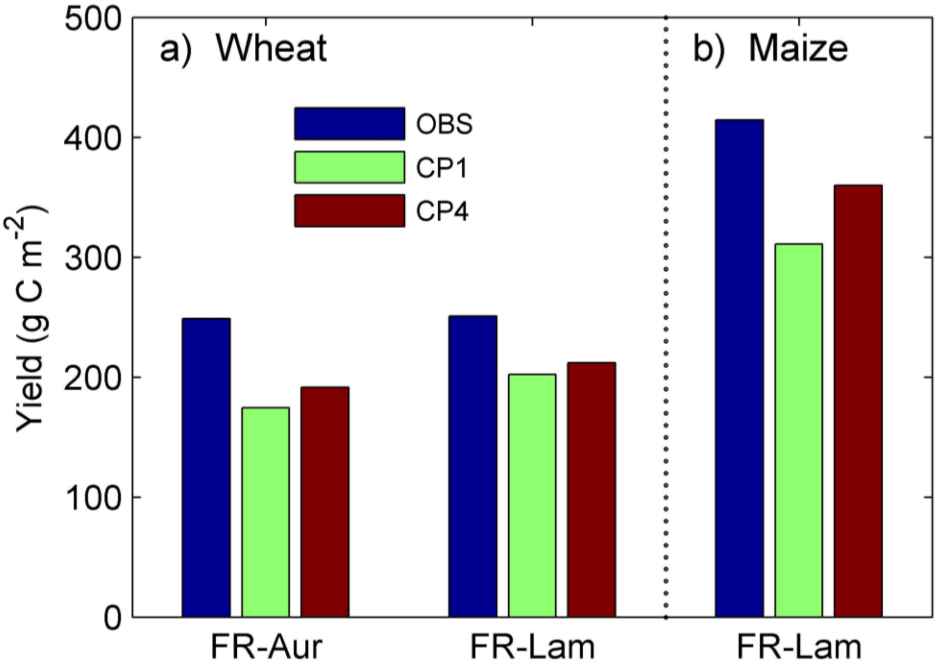

a) Wheat
b) Maize
OBS
CP1
CP4
Yield (g C m-2)
500
400
300
200
100
0
FR-Aur
FR-Lam
FR-Lam

Fig. 7

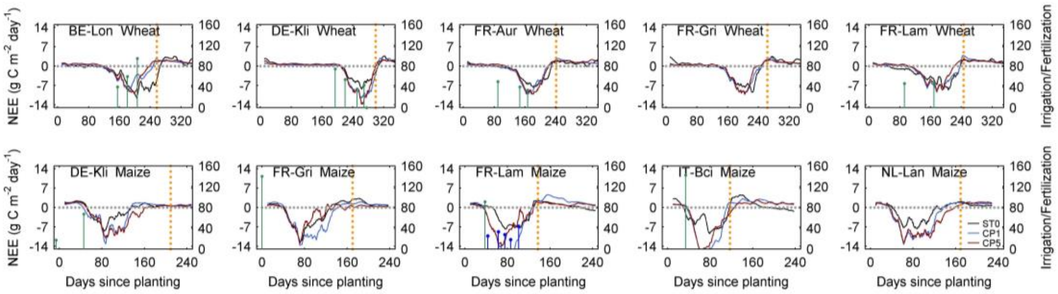

BE-Lon Wheat
DE-Kli Wheat
FR-Aur Wheat
FR-Gri Wheat
FR-Lam Wheat
DE-Kli Maize
FR-Gri Maize
FR-Lam Maize
IT-Bci Maize
NL-Lan Maize
NEE (g C m^{-2} day^{-1})
Irrigation/Fertilization
14
7
0
-7
-14
160
120
80
40
0
0
80
160
240
320
Days since planting
ST0
CP1
CP5

Fig. 8

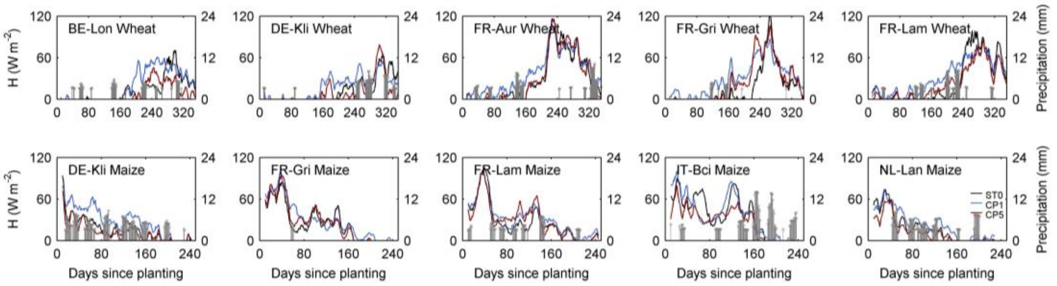

BE-Lon Wheat
DE-Kli Wheat
FR-Aur Wheat
FR-Gri Wheat
FR-Lam Wheat
DE-Kli Maize
FR-Gri Maize
FR-Lam Maize
IT-Bci Maize
NL-Lan Maize
H (W m-2)
Precipitation (mm)
120
60
0
24
12
0
0
80
160
240
320
Days since planting
ST0
CP1
CP5

Fig. 9

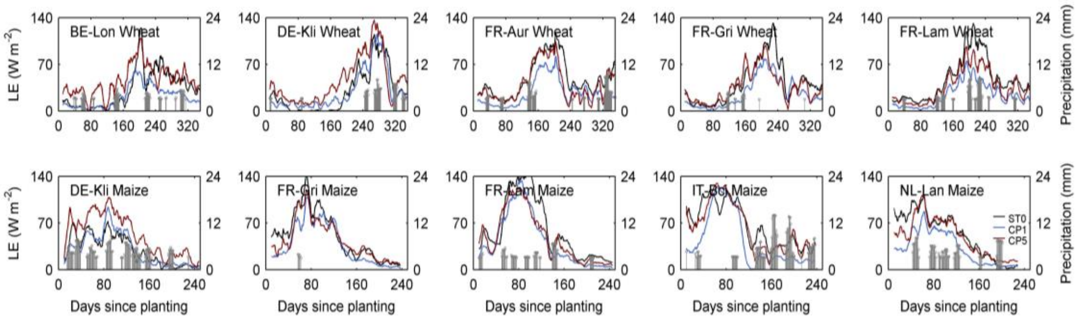
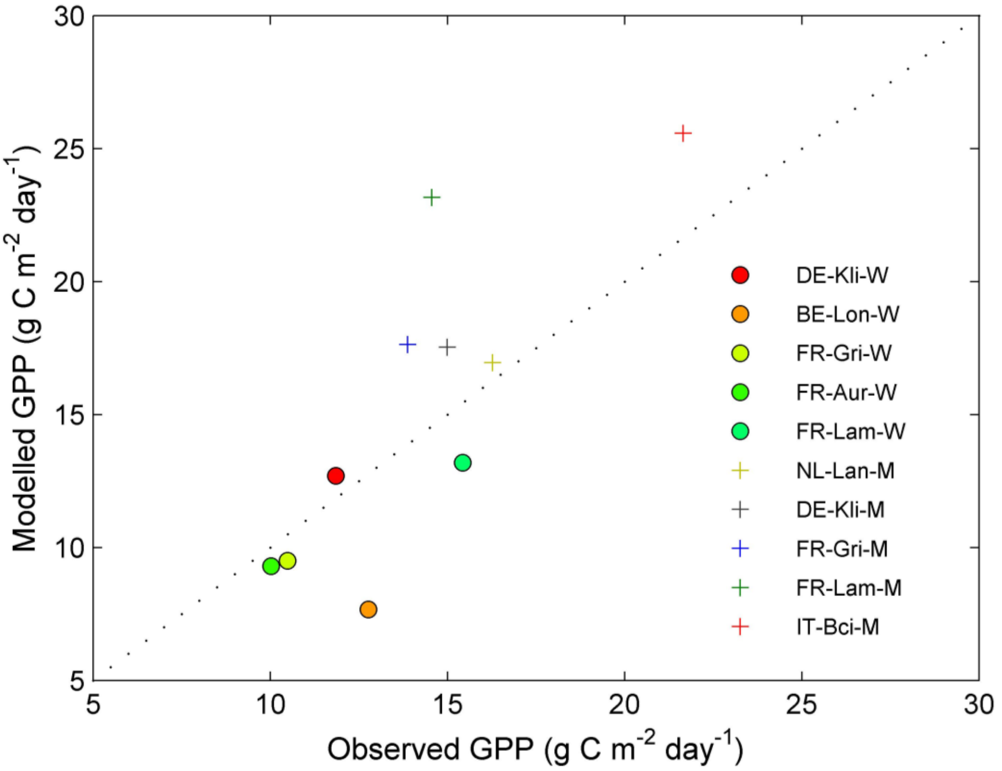

BE-Lon Wheat
DE-Kli Wheat
FR-Aur Wheat
FR-Gri Wheat
FR-Lam Wheat
DE-Kli Maize
FR-Gri Maize
FR-Lam Maize
IT-BCi Maize
NL-Lan Maize
LE (W m^{-2})
Precipitation (mm)
Days since planting
0
70
140
0
12
24
0
80
160
240
320
ST0
CP1
CP5

Figure 10.



30
25
20
15
10
5
Modelled GPP (g C m^{-2} day^{-1})
5
10
15
20
25
30
Observed GPP (g C m^{-2} day^{-1})
DE-Kli-W
BE-Lon-W
FR-Gri-W
FR-Aur-W
FR-Lam-W
NL-Lan-M
DE-Kli-M
FR-Gri-M
FR-Lam-M
IT-Bci-M