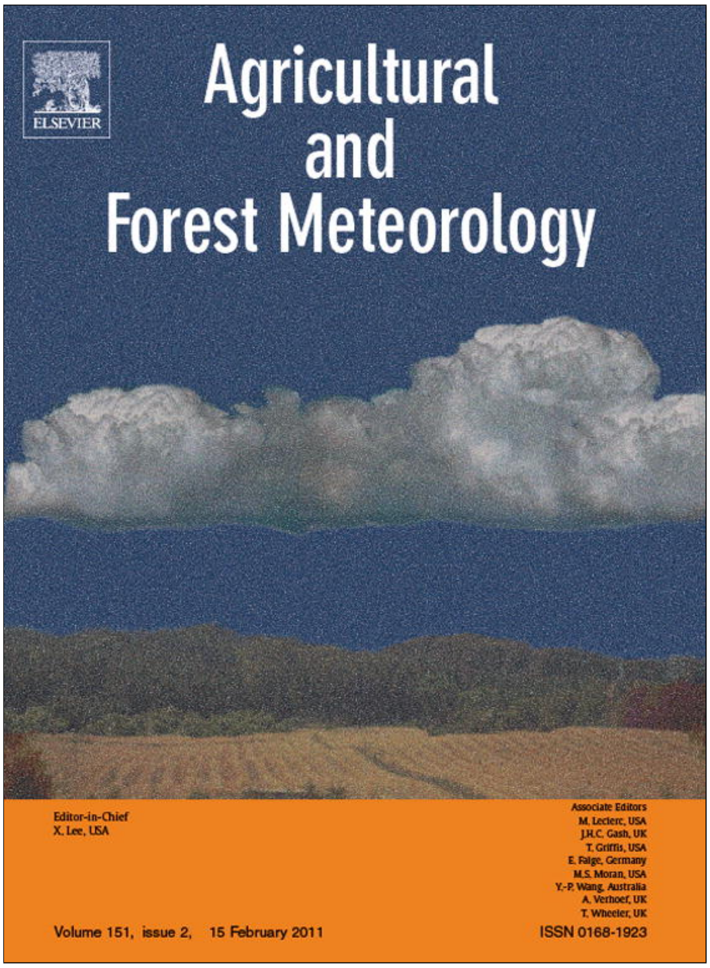
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# Simulating dynamic crop growth with an adapted land surface model – JULES-SUCROS: Model development and validation

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ABSTRACT

The increasing demand for ecosystem services, in conjunction with climate change, is expected to significantly alter terrestrial ecosystems. In order to evaluate the sustainability of land and water resources, there is a need for a better understanding of the relationships between crop production, land surface characteristics and the energy and water cycles. These relationships are analysed using the Joint UK Land Environment Simulator (JULES). JULES includes the full hydrological cycle and vegetation effects on the energy, water, and carbon fluxes. However, this model currently only simulates land surface processes in natural ecosystems. An adapted version of JULES for agricultural ecosystems, called JULES-SUCROS has therefore been developed. In addition to overall model improvements, JULES-SUCROS includes a dynamic crop growth structure that fully fits within and builds upon the biogeochemical modelling framework for natural vegetation. Specific agro-ecosystem features such as the development of yield-bearing organs and the phenological cycle from sowing till harvest have been included in the model. This paper describes the structure of JULES-SUCROS and evaluates the fluxes simulated with this model against FLUXNET measurements at 6 European sites. We show that JULES-SUCROS significantly improves the correlation between simulated and observed fluxes over cropland and captures well the spatial and temporal variability of the growth conditions in Europe. Simulations with JULES-SUCROS highlight the importance of vegetation structure and phenology, and the impact they have on land–atmosphere interactions.



## 1. Introduction

Nearly 40% of the Earth's land surface is currently managed for agricultural production, either through growing crops for food, bioenergy and other products, or by raising animals on land devoted to pasture (Ramankutty and Foley, 1999; Foley et al., 2005). The increasing demand for ecosystem services, in conjunction with climate change, are expected to significantly alter terrestrial ecosystems and, by consequence, the energy, water, and carbon fluxes between land and the atmosphere (Foley et al., 2005). In order to evaluate the potential severity of the sustainability issues that we will face in the near future, there is a need for a better understanding of the relationships between crop production, land–surface characteristics, and energy and water cycles.

The replacement of grasslands and forests by agricultural land use has induced significant changes to the carbon, water, and energy cycles (Foley et al., 2005; Pielke, 2005). Those shifts in water and energy balance are manifested through changes in evapotranspiration and surface run-off, phenology, and net radiation, and the partitioning of sensible and latent heat fluxes (Twine et al., 2004; Foley et al., 2005). Twine et al. (2004) showed that the conversion of grassland to winter wheat in the Mississippi Basin increases the annual net radiation by 19% and the annual evapotranspiration by 7%.

Coupled vegetation climate modelling experiments have shown that the differences in structural and physiological characteristics between natural and agricultural vegetation, *i.e.* albedo, surface roughness, rooting depth, leaf area and canopy resistance, alter the physical land surface properties and the biogeochemical cycles, causing feedbacks to climate (Bonan, 1999; Betts, 2001; Brovkin et al., 2006; Bonan, 2008). In most of these studies, grass has been used as a proxy to represent agricultural vegetation given their structural and physiological similarities. In addition to this, the vegetation structure and phenology have often been prescribed, making it difficult to project the ecosystem response to future changes in environmental conditions.

To better represent the growth, development and harvesting of crops in relation to prevailing meteorological forcings and man-

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agement practices, crop production models have been coupled to Global Dynamic Vegetation Models (Kucharik, 2003; Gervois et al., 2004; Osborne et al., 2007). The sensitivity studies carried out with these models have highlighted the importance of using a dynamic interactive crop growth module in climate modelling (de Noblet-Ducoudre et al., 2004; Osborne et al., 2009). Osborne et al. (2009) found that the seasonality and the inter-annual variability of crop growth and development have a significant effect on the climate through the land surface properties, which in turn can feedback on crop production.

However, to better understand and quantify the response of the energy, water and carbon fluxes to change from natural to agricultural ecosystems, it is necessary to represent growth and functioning of both ecosystems in a single consistent framework (Bondeau et al., 2007). Crops and natural vegetation need to share the same fundamental biophysical and physiological functions. In addition to that, these DGVMs need to be tested and validated against a range of field observations in order to refine and improve model performances (Kucharik et al., 2006; Bonan, 2008). To date, a small number of published studies have evaluated the water, carbon, and energy balance of DGVM's at cropland field sites. To our knowledge, none have quantified the accuracy and level of error associated with the representation of dynamic crop growth and development.

As mentioned by Kucharik et al. (2006) the evaluation of the models can be performed at the local scale using data from the FLUXNET network. FLUXNET is a global network of micrometeorological flux measurement sites that measure the exchange of carbon dioxide, water vapor, and energy between the biosphere and the atmosphere (Baldocchi et al., 2001). The FLUXNET network provides the time and space variability of the fluxes above different surface and vegetation types. One of its primary goal is to provide time series of carbon, water and energy fluxes as well as meteorological, plant, and soil data at a large number of locations over the world.

The goal of this study is to evaluate whether the explicit representation of crops in a land surface model yields better accuracy and a more consistent response to environmental change. In particular, we estimate the effect of interactively simulating growth and development of agricultural vegetation on the spatial and temporal variability of fluxes between the surface and the atmosphere. This paper describes the development and the validation of JULES-SUCROS, an adapted version of the land surface model JULES (Cox et al., 1999) that, in addition to overall model improvements, includes a dynamic crop growth structure that fully fits within the biogeochemical modelling framework for natural vegetation of JULES.

The paper covers the following items: the land surface model JULES and the FLUXNET data are described in Section 2; Section 3 presents the model parametrisations, the model development and the approach for model evaluation; the results of this evaluation are presented and discussed in Section 4; the conclusion of this study is summarised in Section 5.

## 2. Material

### 2.1. The land surface model JULES

In this study, the relationships between crop growth, land surface and water and energy cycles are analysed using the Joint UK Land Environment Simulator (JULES) (Cox et al., 1999). JULES is a UK community land surface model. It was originally designed to represent the land surface in UK weather and climate models, but has been increasingly used for other purposes such as impact studies (Betts, 2007; Harrison et al., 2008). JULES has shown to improve the simulation of global surface climate when included in a climate model (Cox et al., 1999).

JULES calculates water, $CO_2$, momentum and energy fluxes between the land surface, including vegetation, and the atmosphere. It has a tiled model of sub-grid heterogeneity with separate surface temperatures, short-wave and long-wave radiative fluxes, sensible and latent heat fluxes, ground heat fluxes, canopy moisture content, snow mass and snow melt. JULES has five vegetation tiles representing five different Plant Functional Types (PFTs: broad-leaf trees, needle-leaf trees, C3 (temperate) grass, C4 (tropical) grass, shrubs) and it has four non-vegetated surface tiles (urban, inland water, bare soil and ice). As JULES does not explicitly simulate crop growth, crop areas are treated as natural grass.

In JULES, the biophysical state of each PFT is characterised by a leaf area index LAI, canopy height, rooting depth. The LAI and canopy height are either constant throughout the annual cycle or prescribed using remote sensing data, and they both vary spatially, while the rooting depth does not vary temporally nor spatially. The rooting depth is used to determine the available soil moisture for the vegetation within each soil layer. The 4 soil layers have specific hydraulic and thermodynamic properties. Soil water can be extracted through plant transpiration from the 4 layers and by soil water evaporation from the top soil layer.

The surface fluxes of moisture and heat are functions of the atmospheric boundary conditions. Potential values are limited by an aerodynamic resistance. The water extracted from the soil must go through an additional surface resistance. The evaporation from the top soil layer is limited by a soil resistance and the transpiration through the canopy is limited by a stomatal resistance. The exchange of $CO_2$ between plants and the atmosphere is also regulated by this stomatal resistance (Cox et al., 1998), which is a function of environmental conditions and atmospheric $CO_2$ concentration (Jacobs, 1994). This implies that photosynthesis and transpiration are strongly linked. In addition, both depend on the amount of available energy. The carbon, water and energy fluxes are thus coupled to each other.

JULES uses a biochemical approach to estimate photosynthesis. It is based on the model of Collatz et al. (1991) for C3-type photosynthesis and Collatz et al. (1992) for C4-type photosynthesis. This model describes the rate of $CO_2$ assimilation as limited by enzyme kinematics, in particular the amount of Rubisco; electron transport, which is a function of available light; and the capacity to transport or utilise photosynthetic products. The Rubisco-limited rate and the transport-limited rate are a function of the maximum rate of carboxylation of Rubisco. In JULES the latter depends on the leaf temperature and the leaf nitrogen concentrations, which is constant per PFT.

This potential leaf photosynthesis rate is reduced under moisture stressed conditions. The actual leaf photosynthesis rate is then up-scaled to the canopy level by assuming that photosynthesis is proportional to the absorbed active radiation, which is a function of the LAI. Part of the carbon assimilated during the photosynthesis (Gross Primary Productivity, GPP) is used to maintain the existing biomass. This is called the maintenance respiration, $R_{pm}$. The remaining part is converted into structural dry matter (Net Primary Productivity). In the process of conversion, part of the weight is lost in growth respiration, $R_{pg}$. So, $NPP = GPP - (R_{pm} + R_{pg})$.

In JULES, the growth respiration $R_{pg}$ is assumed to be a fixed fraction of $GPP - R_{pm}$. The maintenance respiration $R_{pm}$ is the sum of the respiration from leaves, stem and root, which are all function of the leaf temperature and the leaf nitrogen concentration. Leaf maintenance respiration is limited under moisture stress conditions, while root and stem respirations are assumed to be independent of soil moisture. The maintenance respiration is independent of the accumulated carbon within the vegetation tissues (Cox et al., 1999). The stem respiration however depends on the

**Table 1**
Summary of ecological, climatic, and soil conditions at the FLUXNET sites selected for this study.

| Site name and location | Klingenberg (DE) | Gebesee (DE) | Lonzée (BE) | Grignon (FR) | Auradé (FR) | Lamasquère (FR) |
|---|---|---|---|---|---|---|
| Latitude | 50,89289856 | 51,10010147 | 50,55220032 | 48,84400177 | 43,54940033 | 43,49330139 |
| Longitude | 13,52250004 | 10,91429996 | 4,744939804 | 1,95243001 | 1,10777998 | 1,237220049 |
| Elevation | 478 m | 161.5 m | 167 m | 125 m | NA | NA |
| Landcover (IGBP) | Cropland | Cropland | Cropland | Cropland | Cropland | Cropland |
| Climate | Temperate–continental | Temperate–continental | Temperate–maritime | Temperate–maritime | Temperate–mediterranean | Temperate–mediterranean |
| Avg. air temp. | 7.13 °C | 8.74 °C | 9.44 °C | 10.02 °C | 12.16 °C | 12.69 °C |
| Min. – max. temp. | 1.63–13.36 °C | 4.76–12.65 °C | 5.62 °C–13.45 °C | 6.27–14.49 °C | 7.27–17.13 °C | 7.81–17.69 °C |
| Precipitation | 702.02 mm | 443.94 mm | 843.34 mm | 769.21 mm | 673.34 mm | 702.83 mm |
| FAO soil class | Pseudogley | chernozem | luvisol | Luvisol | NA | NA |
| Specific soil texture (clay:silt:loam), dominant soil texture observations | (c: 90%, sand: 1.5%, silt: 7.5%) | (Clay: 30%) | (Clay: 20%, silt: 72%) | silt loam (clay: 18.8%, silt: 71.3% | Loam | Clay loam |
| Refs. | Tittebrand et al. (2009) | Anthoni et al. (2004) | Moureaux et al. (2006, 2008), Hoyaux et al. (2008) and Aubinet et al., 2009 | Lehuger et al. (2007) | Beziat et al. (2009) | Beziat et al. (2009) |

height of the canopy. This implies that the LAI and the height of the canopy have to be consistent with each other to correctly simulate the plant maintenance respiration, and by consequence the NPP.

The vegetation dynamic component of JULES, TRIFFID (Cox, 2001), is disabled in this study. The areal fraction of each PFT is held static throughout the experiments since the area occupied by cropland depends mainly on anthropogenic factors rather than on competition between vegetation types. In addition, TRIFFID has only a simplified representation of phenology for tree PFT's (Cox, 2001), and is therefore not usable for grass and annual crops. A more detailed description of the model can be found in Essery et al. (2001).

### 2.2. FLUXNET sites data sets

FLUXNET is a global network of micrometeorological tower sites that use the eddy covariance method (Aubinet et al., 2000) to measure the exchanges of carbon dioxide, water vapor and energy between terrestrial ecosystems and the atmosphere. At present, over 400 tower sites are operating on a long-term and continuous basis. In addition to flux measurements, vegetation, soil, hydraulic and meteorological characteristics at the tower sites are collected.

In this study 6 European cropland FLUXNET sites have been selected. At these sites wheat has been grown during at least one season since the flux measurements are operational. These sites are located in three distinct European agro-climatic zones (Bouma, 2005); Mediterranean, Maritime and North-East Europe. A summary of the soil and key climatic and ecological conditions found at these sites is given in Table 1 (FLUXNET, 2009).

The sites of Klingenberg (Kli) and Gebesee (Geb) are both located in the Eastern part of Germany. This region is characterised by a temperate continental climate. Wheat was grown in Klingenberg during the growing season of 2005–2006 and in Gebesee during the growing season of 2006–2007. The site of Lonzée (Lon), in Belgium, and Grignon (Gri), in the North of France, experience a more maritime temperate climate. In Lonzée, wheat was grown during the growing seasons of 2004–2005 and 2006–2007, while in Grignon it was grown during the growing season of 2005–2006. The last two sites, Lamasquère (Lam) and Auradé (Aur), both located in South West of France, are characterised by a Mediterranean climate. At these sites wheat was grown during the growing seasons of 2006–2007 and 2005–2006, respectively.

At all sites, the exchanges of carbon dioxide ($CO_2$), water vapour and energy were measured above the cropland using the eddy covariance method at half-hourly time-steps. Instrumentation and data collection procedures are described in Aubinet et al. (2000) and Baldocchi et al. (2001). References for sites specific measurements are given in Table 1. The daily fluxes have been used to evaluate the latent and sensible heat as well as the carbon exchanges simulated with the land surface model JULES. The FLUXNET data set also provides all the meteorological variables required to force the model at half-hourly timesteps: global and net radiation, air temperature, air humidity, precipitation, wind speed and surface pressure.

## 3. Method

### 3.1. Model parametrisations: experimental design

Half-hourly micrometeorological observations from the selected FLUXNET sites have been used to drive the land surface model JULES. The hydraulic and thermal properties of the soil have been determined from the soil texture observed at the sites (Table 1). The values for the hydraulic parameters have been taken from the database developed by Wosten et al. (1999). The thermal characteristics and soil albedo values have been taken from the JULES technical report (Essery et al., 2001). The model has been spun-up with the micrometeorological data available for the years prior to the growing season of interest. During the growing season of interest, four separate simulations have been performed for the different cropland FLUXNET sites in order to understand whether the parameter values, the model formulation of the physical and physiological processes or the combination of both affected the model performance for crops.

*JULES with large-scale C3 grass paramaterisation*

In the first set of simulations, all the vegetation parameters of the model have been set to the values used for C3 grass as defined by Essery et al. (2001), except the LAI and the height of the canopy, which by default are user defined. The LAI and the canopy height have been set to the mean values for the land cover type “herbs, forbs, grass” in temperate ecosystems (Breuer et al., 2003), namely 6.2 and 1.35 m, respectively. In JULES, the rooting depth of C3 grass is, by default, set to 0.5 m. This set of simulations is used to evaluate the large scale C3 grass parameterisation to simulate fluxes over temperate cropland.

*JULES with large-scale C3 crop paramaterisation*

In the second set of simulations, the vegetation parameters have been adapted to crops. The LAI, height and rooting depth have been set to the mean values determined by Breuer et al. (2003) for the land cover type "crop" in temperate ecosystems. These values are respectively 3.8, 1.44 m and 1.43 m. To parameterise the leaf-level photosynthesis equations for crops, the maximum rate of carboxylation at 25 °C has been set to 60 μmol $m^{-2}$ $s^{-1}$ (Wullschleger, 1993) instead of 48 μmol $m^{-2}$ $s^{-1}$, as defined in JULES for C3 grass. This has been achieved by increasing the leaf nitrogen concentration by 25% (Schulze et al., 1994). In addition to the changes made to some vegetation parameters, the infiltration enhancement factor has been reduced by 50%. A range of authors have reported a 50% decrease in infiltration rate between natural and managed ecosystems due to the use of heavy machinery on agricultural land (Ndiaye et al., 2007; House et al., 2001). This set of simulations is used to evaluate the C3 crop parametrisation to simulate fluxes over temperate cropland.

*JULES with site-specific phenology*

In the third set of experiments, time series of measured LAI values have been used to prescribe the crop phenology. These data were only available at Lonzée for the growing season of 2004–2005 and at Klingenberg for the growing season of 2005–2006. Since the LAI, canopy height and rooting depth need to be consistent with each other, as mentioned in Section 3.1, time series of crop height and rooting depth have been extrapolated from the LAI. The formulation of (Debaeke, 1995) has been used to compute the height:

$$h = h_{max}\sqrt{\frac{LAI}{LAI_{max}}}, \qquad (1)$$

where $h$ is the actual height of the canopy and $h_{max}$ is the maximum canopy height. The actual rooting depth, $d_r$ is assumed to be proportional to $h$ with a factor $d_r/h_{max}$ (Wu et al., 1999). The maximum rooting depth, $d_{rmax}$, and the maximum canopy height, $h_{max}$, for wheat have been set to 1.43 m and 1.44 m (Breuer et al., 2003), respectively. Some minor modifications to JULES have been performed to allow the LAI, height and rooting depth to be zero after harvest. In the original model settings, it assumed that a vegetation tile is never bare. This set of simulations is used to evaluate the importance of crop phenology when simulating the interaction of crop growth with the land surface.

*JULES-SUCROS with dynamic crop growth*

In the fourth and last set of simulations, only site-specific half hourly micrometeorological data and soil textural information have been used as model drivers. The simulations have been performed with JULES-SUCROS, an adapted version of JULES that explicitly simulates crop growth and development and its interactions with the environment. The phenology is no longer prescribed but simulated. JULES-SUCROS is used to study crop growth, development and production in relation to the prevailing environmental conditions as well as the impact of growth and development on the land surface.

### 3.2. Model development: dynamic crop growth structure within JULES

In this section, the development of the land surface model JULES-SUCROS is described. Since most of the crop modules have been derived from the crop model SUCROS (Goudriaan and van Laar, 1994), the resulting model has been denoted JULES-SUCROS. The generic crop model SUCROS has originally been developed for potential production situation (van Keulen et al., 1982; Penning de Vries and van Laar, 1982; Goudriaan and van Laar, 1994; van Laar et al., 1988). SUCROS is a mechanistic model that simulates crop growth on the basis of the underlying processes, such as $CO_2$ assimilation and respiration, as influenced by environmental conditions. The crop phenological development determines the crop life cycle and regulates the daily growth of a specific crop from sowing or emergence to maturity.

To obtain JULES-SUCROS, two types of adaptations have been made to the land surface model JULES. On the one hand, some basic adaptations have been performed to allow variables to vary consistently with each other along the growing season. Many processes in JULES depend on the LAI, canopy height and rooting depth, and have to respond consistently to changes in these parameters values. In addition to that, the parameterisation for bare soil on a vegetated tile has been implemented.

On the other hand, a new set of subroutines has been added to JULES to represent crop growth and development, and sowing and harvest dates. The sowing date depends on the prevailing meteorological conditions and farmer's decision. The development rate of the dynamic crop is determined by temperature, while the growth rate is organ specific (root, stem, leaf, and storage organs) and depends on the phenological stage and the amount of available assimilates, which are both determined by the environmental conditions. Senescence and retranslocation of dry matter are represented as well. The biophysical parameters, *i.e.* LAI, crop height, and rooting depth, which link the vegetation and the land surface, are dynamic and consistent with the growth and development of the crop organs.

JULES-SUCROS incorporates crops and natural vegetation within the same biogeochemically consistent numerical framework. It is important to note that the model has only been parameterised for a generic (winter) wheat crop. This is mainly because wheat is the most important crop, covering 22% of the total cultivated area of the world (Leff et al., 2004) and is very extensively grown in Europe. The model has not been tuned against observations to optimise the results.

In JULES-SUCROS, the dry weights of the plant organs are obtained by integration of their growth rates over time. By consequence, in addition to the interactions between crop growth and the land surface, the model can be used to explore the impact of environmental changes on crop productivity. The potential yield can be interpolated from the amount of biomass accumulated into the storage organs. In JULES-SUCROS, only environmental factors are considered under the assumption that optimum management practices are applied. The different subroutines and adaptations made to JULES are described in more detail below.

#### 3.2.1. Sowing date and phenological development

*Sowing date.* In JULES-SUCROS, wheat is sown during autumn, once the average daily temperature drops below 10 °C (Porter et al., 1987). The seedling emergence starts 15 days after sowing. At emergence, the amounts of dry matter (DM) in leaves, stems and roots are set to the initial value of 0.5 g DM $m^{-2}$, 0.3 g DM $m^{-2}$ and 0.8 g DM $m^{-2}$, respectively. The initial specific leaf area is set to 0.022 (van Laar et al., 1988).

*Phenological development.* In JULES-SUCROS, the phenological development starts at seedling emergence. The development stage (DVS) is arbitrarily set to 0 at seedling emergence, to 1 at flowering and to 2 at maturity (van Heemst, 1986). It is assumed that the annual crop is harvested once it has reached maturity. The DVS is calculated as the integral of the development rate. For wheat growing at 20 °C, this rate is equal to $1.5 \times 10^{-2}$ $d^{-1}$ during the vegetative phase ($0 < DVS < 1$) and to $2.55 \times 10^{-2}$ $d^{-1}$ during the generative phase ($DVS > 1$) (Penning de Vries et al., 1989). Under temperate climatological conditions, temperature is the main environmental factor affecting the rate of development. The relationship between the development rate and the daily temperature is crop specific (see the work of Penning de Vries et al., 1989 for more details on wheat).

*Vernalisation.* Winter wheats have an absolute requirement for vernalisation, which is the exposure to low, nonfreezing temperatures, before they can develop beyond the vegetative phase. The vernalisation subroutine in JULES-SUCROS is based on the generalised nonlinear vernalisation response function for winter wheat developed by Streck et al. (2003):

$$f_v = \frac{(\mathrm{VD})^5}{[(22.5)^5 + (\mathrm{VD})^5]}, \tag{2}$$

where VD is the duration of the exposition to vernalising temperatures. A VD of one is attained when the crop is exposed to the optimal temperature for vernalisation (4.9 °C) for one day. As temperatures depart from the optimum, only a fraction of 1VD is accumulated by the crop. Below −1.3 °C and above 15.7 °C no VD is accumulated. $f_V$ is zero once DVS > 0.4 or VD = 50. To account for the effect of VD on the development rate of the crop, this rate is multiplied by $f_V$, which varies between 0 and 1.

### 3.2.2. Crop growth and biomass partitioning

*Maintenance respiration.* In Section 3.1, it is mentioned that the respiration rate computed in (standard) JULES is inconsistent with the actual carbon content of the vegetation. Therefore the modelling approach used for maintenance and growth respiration in JULES has been replaced by the modelling approach of SUCROS to account for the actual dry weight of each organ and the difference in their respiration rate.

In JULES-SUCROS, fixed coefficients of the total dry matter of each organ are used to calculate the maintenance requirements of the various organs of the crop, *i.e.* leaves, stems, roots and storage organs. For wheat these values are set to 0.03, 0.015, 0.015, 0.01, respectively. Higher temperatures accelerate the turnover rates in plant tissue and hence increase the costs of maintenance. A 10 °C increase in temperature increases maintenance respiration by a factor 2 (Penning de Vries and van Laar, 1982). When the crop ages, its metabolic activity decreases and hence its maintenance requirements decrease. This is represented in the model by assuming that maintenance respiration is proportional to the fraction of the accumulated leaf weight that is still green (van Laar et al., 1988). The leaf senescence is described in Section 3.2.3.

*Growth respiration.* During the conversion of the assimilated carbon into structural matter, some weight is lost due to growth respiration. In JULES-SUCROS the amount of assimilates required to produce one unit of dry weight of roots, leaves and stems of an annual crop is set to 1.444, 1.463, and 1.513 g of $CH_2O$ per g of DM, respectively. For wheat grains, 1.415 g of $CH_2O\,g^{-1}$ is required to produce 1 g of DM (Penning de Vries and van Laar, 1982; Penning de Vries et al., 1989).

*Partitioning and retranslocation.* In JULES-SUCROS the allocation of dry matter over the various plant organs (root, stem, leaf and storage organs) is described by fixed distribution factors, which depend on the development stage of the crop. The values for these factors have been taken from Penning de Vries et al. (1989). After anthesis (DVS > 1), 20% of the stem weight is eventually retranslocated to the storage organs. Leaves also lose weight during senescence. This process is described in the next section.

### 3.2.3. The biophysical parameter estimations

*Leaf expansion and senescence.* During juvenile growth, the increase in leaf area is mainly determined by temperature. In these early stages, the LAI increases exponentially as it satisfies the following equation:

$$\frac{d}{dt}(\mathrm{LAI}) = \mathrm{RGRL} \times T_{\mathrm{eff}} \times \mathrm{LAI}(t) \tag{3}$$

where LAI($t$) is the current leaf area, RGRL is the relative growth rate of leaf area per degree-day, $T_{\mathrm{eff}}$ is the daily effective temperature. The value of RGRL is set to 0.00817 $\mathrm{d}^{-1}$ (van Diepen et al., 1988). $T_{\mathrm{eff}}$ is defined as the actual temperature subtracted by a certain threshold temperature, which is set to 2 °C for wheat. In later development stages, leaf area expansion is increasingly restricted by the supply of assimilates. In JULES-SUCROS, once LAI > 0.75 or DVS > 0.3, the model calculates the growth of leaf area by multiplying the simulated increase in leaf weight by the specific leaf area of new leaves.

The senescence rate of LAI is described on the basis of a relative death rate. The relative death rate is the maximum of an ageing death rate and a self-shading death rate. The latter equals zero for LAI smaller than 4, and increases linearly with increasing LAI until a maximum value of 0.03 at a LAI of 8 and above. The death rate due to ageing equals zero for DVS < 1. Once DVS equals 1 this rate increases with increasing DVS value and depends on the ambient temperature as well. For more details on the dependency of the ageing death rate on DVS and temperature, we refer to the work of van Laar et al. (1988). The death rate of leaves is defined as the senescence rate of the leaves times the weight of the green leaves.

In cereals, the ears also contribute to the photosynthesis. This is called the Ear Area Index, EAI. The value of the EAI depends on the DVS of the crop. From emergence until a DVS of 0.8, the EAI is equal to 0. Once the DVS equals 0.8, the EAI is equal to a fixed proportion of the total above-ground dry matter. This fraction is set to $0.63 \times 10^{-3}$. Once the DVS equals 1.3, the EAI decreases with the same rate as the ageing death rate of leaves.

*Height and rooting depth.* In JULES-SUCROS, the height of the canopy is a function of the amount of stem and leaf biomass, according to the allometric relationship defined by Arora and Boer (2005):

$$h(t) = (C_S(t) + C_L(t))^{0.385} \tag{4}$$

where $h$ is the vegetation height in meters and $C_L$ and $C_S$ are the leaf and stem biomass (in $\mathrm{kg\,C\,m^{-2}}$), respectively.

The rooting depth is obtained from the root biomass using the the formulation developed by Arora and Boer (2003):

$$r_d(t) = \frac{3B^{\alpha}(t)}{b} \tag{5}$$

where $B$ is the root biomass (in $\mathrm{kg\,C\,m^{-2}}$), $b$ = 0.87 is the parameter representing the variable root distribution and $\alpha$ is the "root growth direction" parameter. The value of $\alpha$ depends on the vegetation type and is set to 0.8 for crops.

## 3.3. Model evaluation against FLUXNET data

### 3.3.1. The energy balance closure

A study by Aubinet et al. (2000) has reported a general lack of energy balance closure at the FLUXNET sites with the fluxes of sensible and latent heat being underestimated and/or available energy being overestimated. El Maayar et al. (2008) have therefore suggested to check whether the measurements of energy fluxes satisfy the energy budget closure prior to their use in land surface model evaluation.

The surface energy budget can be expressed as:

$$R_n = H + \lambda E + G, \tag{6}$$

where $R_n$, $H$, $\lambda E$ and $G$ are the net radiation, sensible heat flux, latent heat flux and soil heat flux, respectively. The lack of closure of the energy budget is commonly quantified by the following factor:

$$I = 100\left(\frac{R_n - G}{H + \lambda E} - 1\right) [\%], \quad (7)$$

where it is generally assumed that $R_n$ and $G$ measurements are sufficiently accurate (Twine et al., 2000; Wilson et al., 2002).

In addition to that, the Mean Bias Errors (MBE) allows us to estimate whether the observed latent and sensible heat fluxes tend to over- or underestimate the observed available energy, $R_n + G$. It can be expressed as followed:

$$\mathrm{MBE} = \frac{\sum_{i=1}^{n}((H_i + \lambda E_i) - (R_{ni} - G_i))}{n}, \quad (8)$$

where $n$ the number of observations during one growing season and $i$ the observation at timestep $i$.

The energy budget closure has solely been evaluated for the FLUXNET sites of Klingenberg and Lonzée since the $G$ measurements were only available for these two sites.

### 3.3.2. *Model performance*

At each site, the latent and sensible heat exchanges [W m$^{-2}$] and the GPP [g C m$^{-2}$] simulated at a daily timestep have been tested and validated against the FLUXNET eddy covariance data. If available, instantaneous soil moisture measures at the FLUXNET tower sites have also been used to evaluate the model output. Comparisons between observed and simulated above-ground biomass, yield, sowing and harvest date have only been possible for the simulations with JULES-SUCROS since JULES does not simulate these features.

The model performance has been quantified in several ways. The correlations between measured and simulated GPP, sensible heat flux, latent heat flux and soil moisture have been used to calculate the coefficient of determination, $r$:

$$r = \frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\left(\sum_{i=1}^{n}(O_i - \bar{O})^2 \sum_{i=1}^{n}(P_i - \bar{P})^2\right)^{1/2}}, \quad (9)$$

where $O_i$ and $P_i$ are the individual observed and model simulated values, respectively, and $\bar{O}$ and $\bar{P}$ are the mean of the observed and simulated values, respectively.

This coefficient has been used as a relative index of model performance. The correlation coefficient is a direct measure of how well the observations and simulations vary jointly. The mean bias errors, MBE, already defined in Section 3.3.1, and the Root Mean Squared Error, RMSE, have also been calculated. On the one hand, the MBE calculations provide an estimate of whether the model has tendencies to over-predict (*i.e.*, positive bias) or under-predict (*i.e.*, negative bias) the fluxes with respect to observations. On the other hand, the RMSE is a measure of the deviation between the model and the observations. The latter is used to quantify the accuracy of the simulations and has been computed as follows:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \quad (10)$$

To evaluate the significance of the bias between observed and simulated values, the RMSE has been compared to the natural variability of the values during the growing season of interest. The standard deviation $\sigma$ of the observed values is used as a measure for the natural variability:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(O_i - \bar{O})^2}{n}} \quad (11)$$

The intra-annual performance of the model has been quantified at daily and monthly timesteps. The correlations between measured and simulated anomalies of fluxes between two different FLUXNET sites or growing seasons have been used to determine whether the model could satisfactorily capture the observed spatial and inter-annual variability. Here again, $r$, RMSE and MBE have been computed to quantify the model performance.

## 4. Results and discussion

In this section, we perform a number of simulations to validate JULES-SUCROS against FLUXNET data and highlight the differences in paramaterisation and process representation between the simulations with JULES and JULES-SUCROS.

First, the energy balance closure has been evaluated at the FLUXNET sites of Lonzée and Gebesee. Next, the model performances for the four subsequent experimental designs described in Section 3.1 have been quantified. The simulation carried out with JULES parameterised for C3 grass are denoted 'JULES (grass)', the simulation with JULES parameterised for C3 crop are denoted 'JULES (crop)', the simulations with JULES forced with site specific phenology are denoted 'JULES (crop-seasonal)' and the simulations with JULES-SUCROS are denoted 'JULES-SUCROS'. The results of the simulations with 'JULES (grass)', 'JULES (crop)' and JULES-SUCROS are represented respectively in green, blue and red in Figs. 2–5, and Figs. A.1 and B.1 in Appendix A and B. The results of the simulation with 'JULES (crop-seasonal)' are represented by black diamonds in Fig. 3, and black dots and lines in Figs. A.1 and B.1.

Finally, the sensitivity of the land surface model to cropland versus grassland and to dynamic versus static crop has been evaluated at each site by comparing the simulations with 'JULES (grass)' against 'JULES (crop)', and by comparing the latter with JULES-SUCROS, which includes a dynamic crop growth structure.

### 4.1. *Evaluation of the energy balance*

Fig. 1(a) shows average daily data of $H + \lambda E$ plotted against $H_n - G$. Fig. 1(b) shows average variation of the daily observed energy imbalance. The plots are restricted to the sites of Lonzée in 2005 and 2007 and Gebesee in 2007 since $G$ was only available for these two sites.

Assuming that $R_n$ and $G$ measurements are sufficiently accurate, Fig. 1(a) shows that $H + \lambda E$ is underestimated at both sites. This can be due to an underestimation of $H$ or $\lambda E$ or both. The underestimation is the largest at Lonzée with an MBE value of −17.5 W m$^{-2}$ in 2005 and −24.1 W m$^{-2}$ in 2007. The RMSE values are respectively equal to 23.4 W m$^{-2}$ and 31.7 W m$^{-2}$. At Gebesee, the MBE is equal to −10.8 W m$^{-2}$ and the RMSE is equal to −21.7 W m$^{-2}$. Fig. 1(b) shows that, in absolute values, the imbalance is in fact proportionally larger during the winter than in the summer. This is probably due to the fact that during the winter the amount of available energy is close to the observational error. The annual averages of the absolute energy imbalance for Lonzée-2005, Lonzée-2007 and Gebesee-2007 are respectively equal to 24.8%, 21.3% and 9.5%. These significant energy imbalances imply that the results of the model evaluation have to be interpreted with care.

### 4.2. *Assessment of fluxes above cropland with the C3 grass PFT parameterisation*

The results of the simulation with 'JULES (grass)' have been used to evaluate the validity of the large scale C3 grass parameterisation for simulating carbon and water exchanges above small scale cropland sites.

Fig. 2 shows the correlation between the observed and simulated latent heat flux (W m$^{-2}$), sensible heat flux (W m$^{-2}$), gross

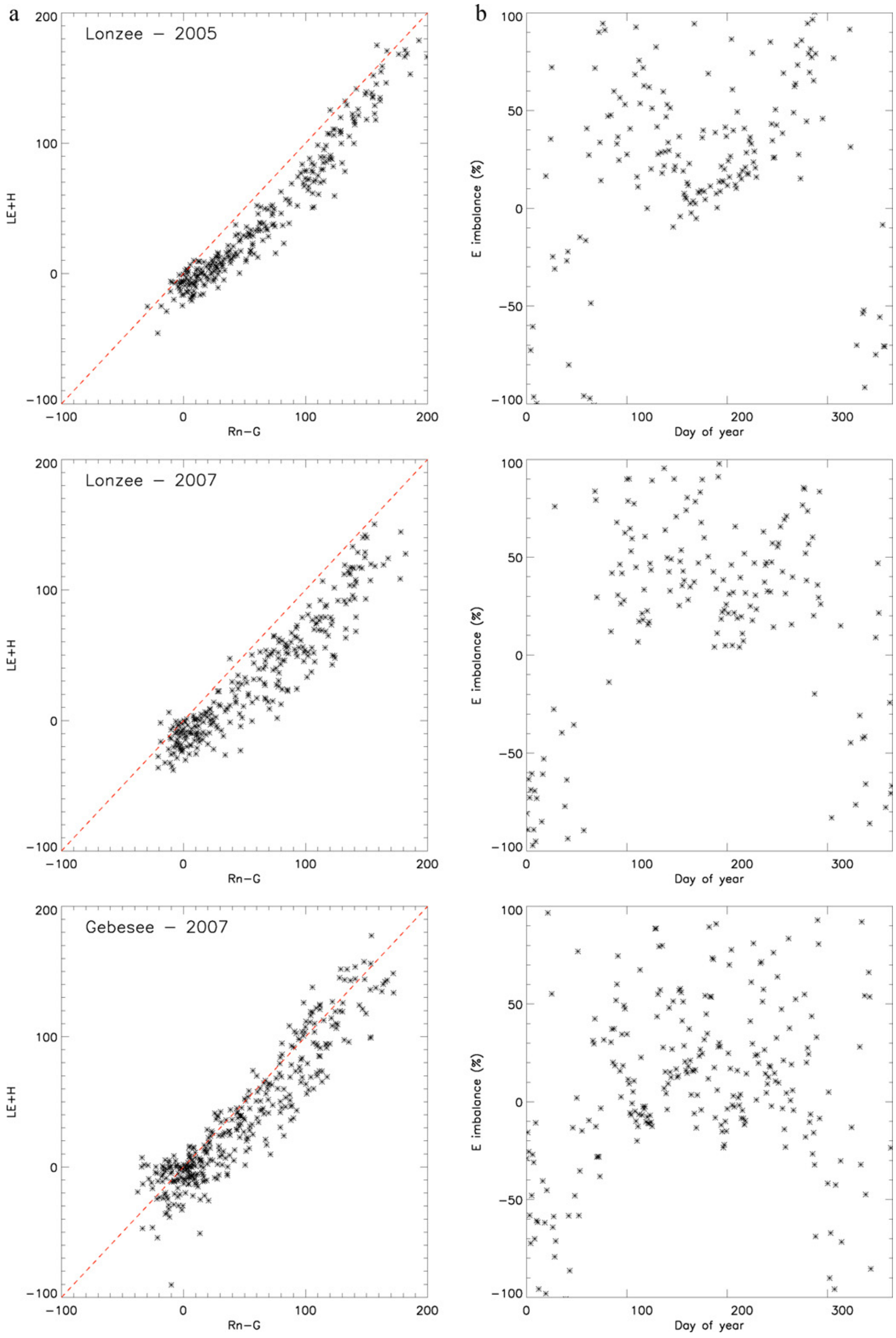


**Fig. 1.** Left panels (a): correlation between observed available energy and fluxes of sensible and latent heat. Right panels (b): time series of the observed energy imbalance. The data represented are daily values for the sites of Lonzée in 2005, 2007 and Gebesee in 2007 (top, middle and bottom panels respectively).

primary productivity ($g\,C\,m^{-2}$) and the percentage of moisture content at saturation within the top 50 cm of the soil. These plots regroup the monthly values for the different sites and growing seasons together.

Fig. 2 shows that the correlations over all FLUXNET sites and growing seasons are the poorest for the percentage of moisture content within the top 50 cm of the soil. The value of the coefficient of determination *r* is less than 0.50. The RMSE is 11.3% and the MBE is 6.9%. This means that the simulated soil moisture content tends to overestimate the observed values. The coefficient of determination *r* for the sensible heat flux is equal to 0.53 and the RMSE is equal to about 15 $W\,m^{-2}$. The simulations tend to underestimate the observed values, given that the MBE is equal to −15.2 $W\,m^{-2}$. The coefficients of determination for the latent heat flux and the GPP are respectively 0.79 and 0.68. The RMSE are respectively 37.7 $W\,m^{-2}$ and 5.6 $g\,C\,m^{-2}$. The simulated latent heat flux and the

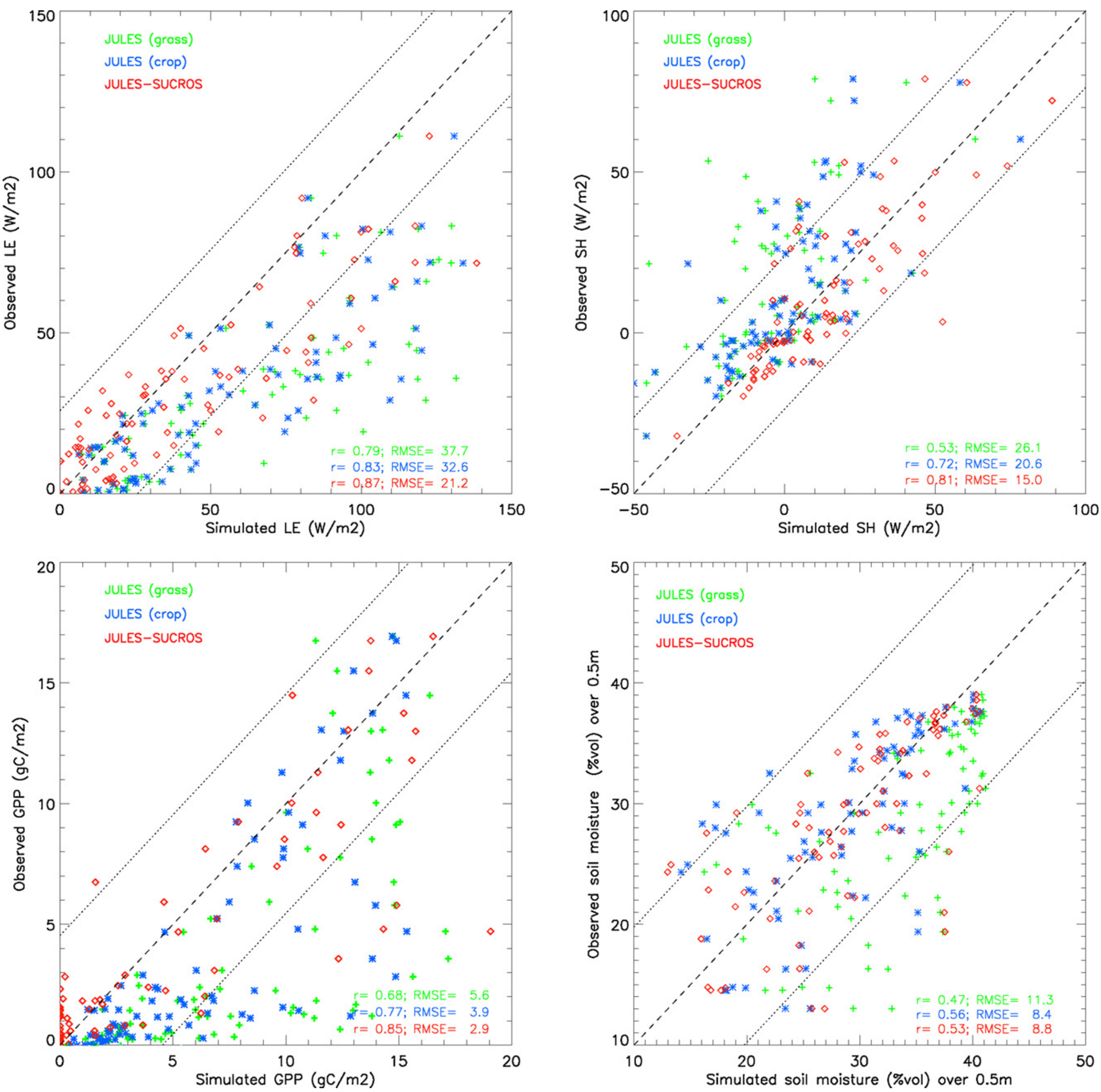


**Fig. 2.** Correlation between the observed and simulated average monthly latent heat flux, sensible heat flux, gross primary productivity and soil moisture within the top 50 cm of the soil. The results have been obtained for the simulations with 'JULES (grass)' (green), 'JULES (crop)' (blue) and 'JULES-SUCROS' (red) during the different wheat growing seasons at the selected FLUXNET sites. The dotted lines represent the 95% interval of the observed latent and sensible heat fluxes, GPP and soil moisture contenet, respectively. All correlations are significant at a 95% interval. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

GPP tend to overestimate the observed values (MBE = 28.8 W m$^{-2}$ and MBE = 4.1 W m$^{-2}$, respectively).

Fig. 3 shows the RMSE between the measured and simulated variables at daily timesteps at each individual site and growing season. The variables represented are the latent heat flux, sensible heat flux, GPP and percentage of soil moisture content within the top 50 cm. The standard deviation of the values measured during the growing season at the different FLUXNET sites are also represented. Fig. 3 shows that the RMSE for the 'JULES (grass)' simulations are, in general, larger than the standard deviation of the measured values (black diamonds in Fig. 3). These results indicate that 'JULES (grass)' is not able to simulate accurately the observed fluxes. The discrepancies are on average the largest at Gebesee, Klingenberg and, to a smaller extent, at Lonzée in 2007. At Lonzée in 2005, the RMSE is smaller or similar to the standard deviations of the observed values. Fig. 4 shows that the correlations between the measured and simulated values vary strongly from one site to another and from one variable to another.

Fig. 5 represents the RMSE between the measured and the simulated monthly latent heat flux, sensible heat flux, gross primary productivity and moisture content within the top 50 cm averaged over all FLUXNET sites and growing seasons. It can been seen that the bias in GPP and fluxes are the largest during the summer and fall, with average maximum RMSE of 70 W m$^{-2}$, 50 W m$^{-2}$ and 9 g C m$^{-2}$. This coincides with the period after crop harvest (see Table 2). Once the crop is harvested, the measured GPP values drop close to zero, while the simulated GPP does not show this pattern. The simulated vegetation continues to assimilate car-

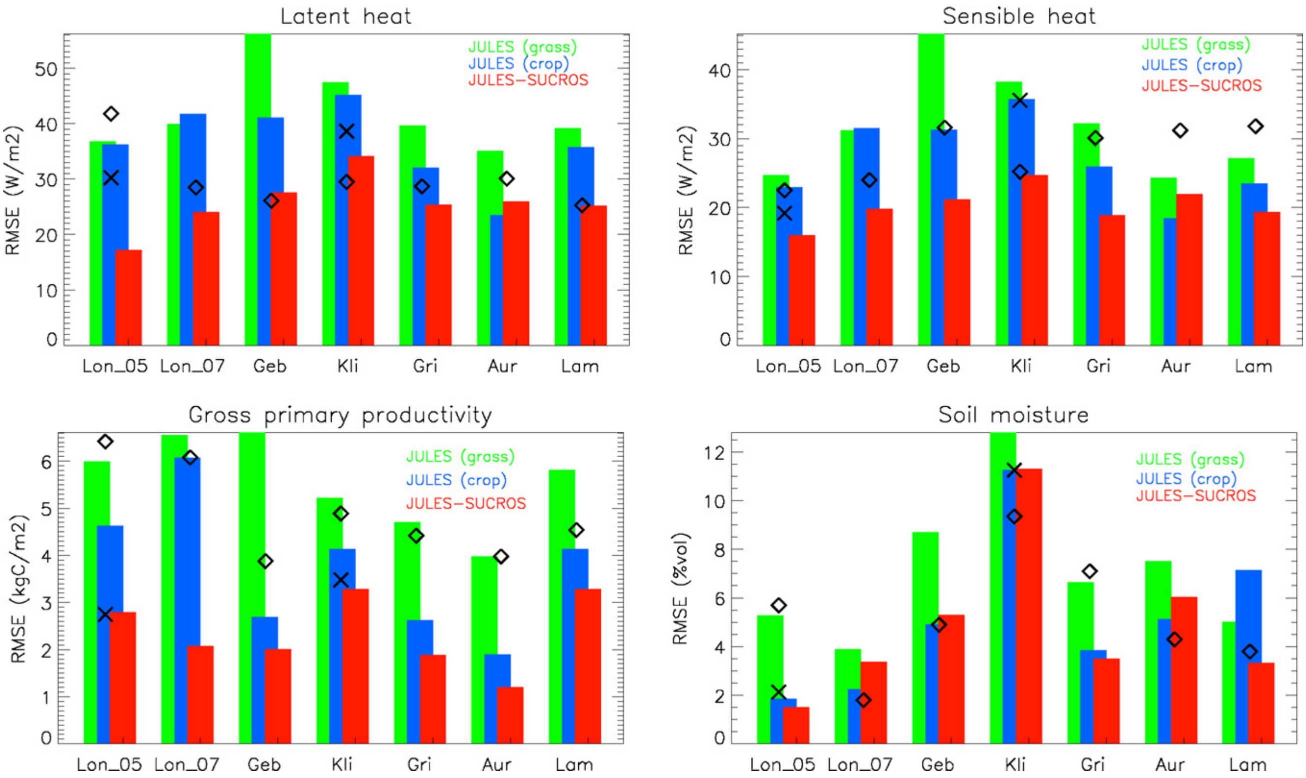


**Fig. 3.** Root mean square error between observed and simulated daily latent heat flux, sensible heat flux, gross primary productivity and soil moisture content. The results have been obtained for the simulations with 'JULES (grass)' (green), 'JULES (crop)' (blue) and 'JULES-SUCROS' (red) during the different wheat growing seasons at the selected FLUXNET sites. The RMSE of the simulations with 'JULES (crop-seasonal) at Lonzée and Klingenberg are represented by ×. The standard deviations of the daily variables measured at the different sites are represented by ◊. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

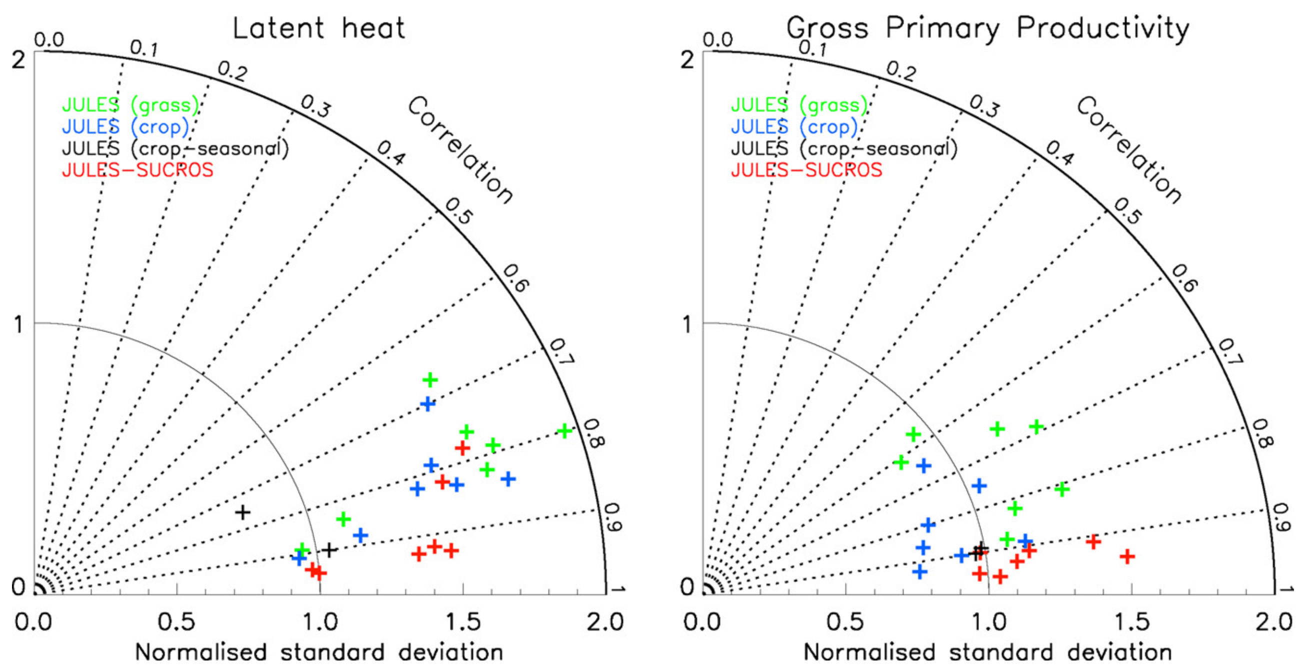


**Fig. 4.** Taylor diagrams (Taylor, 2001) displaying a statistical comparison with the measurements of the simulated daily latent heat fluxes and gross primary productivity. The results have been obtained for the simulations with 'JULES (grass)' (green), 'JULES (crop)' (blue), JULES (crop-seasonal)' (black) and 'JULES-SUCROS' (red) during the different wheat growing seasons at the selected FLUXNET sites. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

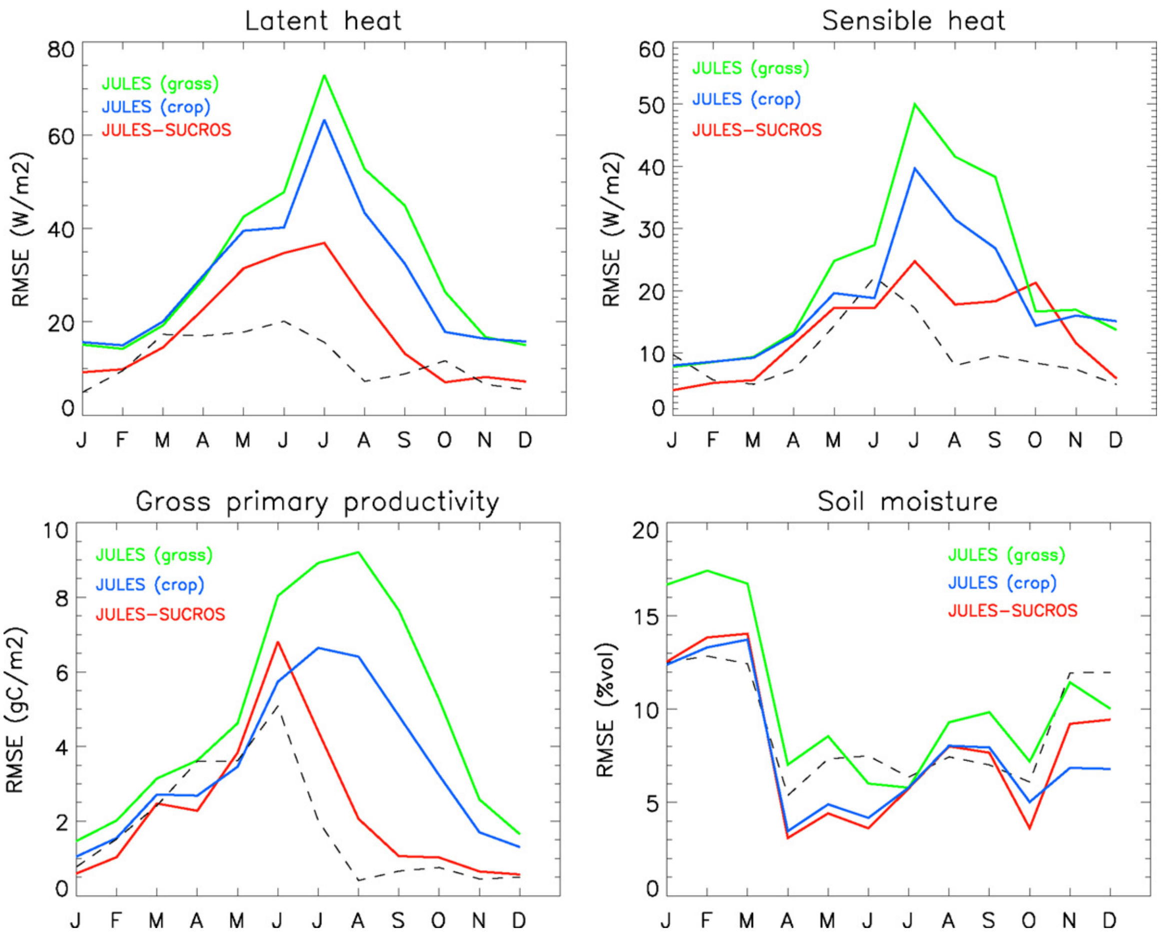


**Fig. 5.** Root mean square error over all FLUXNET sites and growing seasons between measured and simulated monthly latent heat flux, sensible heat flux, gross primary productivity and soil moisture within the top 50 cm. The simulations have been performed with 'JULES (grass)' (green), 'JULES (crop)' (blue) and 'JULES-SUCROS' (red) for the different FLUXNET sites and growing seasons. The standard deviations of the monthly variables measured during the growing season are represented by a dashed line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

bon and to transpire as long as the environmental conditions are favourable.

Overall, these results indicate that 'JULES (grass)' cannot simulate accurately the observed fluxes and does not capture well the seasonal variability. The lack of explicit representation of crop harvest in the model explains a major part of the bias between observed and simulated values.

### *4.3. Assessment of fluxes above cropland with the C3 crop parameterisation*

The results of the simulation with 'JULES (crop)' have been used to evaluate the validity of the large scale C3 crop parameterisation for simulating carbon and water exchanges above small scale cropland sites.

Fig. 2 shows that 'JULES (crop)' performs better than 'JULES (grass)' as it improves the correlation between the measured and simulated variables and reduces the RMSE. The correlation $r$ improves the most for the sensible heat flux with an increase of 36% (significance level $p < 0.05$). For the percentage of soil moisture content and the GPP, the improvements are of 16% and 13%, respectively. The correlation of the latent heat flux has only increased by 5%. The values of the RMSE have decreased the most for the GPP and the soil moisture content, with a drop of 28% and 26%, respectively. Compared to 'JULES (grass)', 'JULES (crop)' has a smaller tendency to overestimate or underestimate the observed values, in particular for the soil moisture as MBE = 1.7 W m$^{-2}$.

Fig. 3 shows that the reduction in RMSE is the largest at Gebesee and, to a smaller extent, at Grignon and Auradé. It is also at these sites that the correlations between measured and simulated values

**Table 2**
Observed and simulated sowing and harvest dates at the FLUXNET sites selected for this study. The simulations have been performed with JULES-SUCROS.

| | Sowing | | | Harvest | | |
|---|---|---|---|---|---|---|
| | Observed | Simulated | Difference | Observed | Simulated | Difference |
| FLUXNET sites | | | | | | |
| Klingenberg | 25/09/05 | 29/10/05 | +4d | 06/09/06 | 14/09/06 | +8d |
| Gebesee | NA | 18/10/06 | NA | NA | 23/08/07 | NA |
| Lonzée | 14/10/04 | 18/10/04 | +4d | 03/08/05 | 10/07/05 | −24d |
| | 13/10/06 | 28/10/06 | +15d | 05/08/07 | 15/07/07 | −21d |
| Grignon | NA | 06/11/05 | NA | NA | 30/08/06 | NA |
| Auradé | 27/10/05 | 02/11/05 | +6d | 29/06/06 | 06/07/06 | +7d |
| Lamasquère | 28/10/06 | 29/10/06 | +1d | 15/07/07 | 08/07/07 | −7d |

have improved the most, in particular concerning the soil moisture content (not shown). The differences between the effect of both parameterisations on the simulated variables are discussed in more details in Section 4.7.

These results indicates that the C3 crop parameterisation is more appropriate than the C3 grass paramaterisation to simulate the fluxes above the selected cropland sites. A reduction of the value of the infiltration rate has reduced the soil moisture content, and by consequence the bias with the observed values. A better representation of the soil moisture content tends to increase the accuracy of the simulated fluxes.

### 4.4. Added value of site-specific crop phenolgy for the land surface model performance

The results of the simulations with 'JULES (crop-seasonal)' have been used to evaluate the importance of crop phenology when simulating the interaction of crop growth with the land surface. Fig. A.1 shows the correlations between observed and simulated latent heat flux, sensible heat flux and GPP simulated with 'JULES (crop-seasonal)' at Klingenberg in 2006, and Lonzée, in 2005.

Forcing JULES with site-specific phenology has improved the accuracy of the simulations at Lonzée. Compared to 'JULES (crop)', the coefficient of determination $r$ for the sensible heat flux and the GPP has significantly increased, respectively by 51% and 12.5% (significance level $p < 0.05$). The drop in RMSE is the most significant for the GPP, going from 4.63 g C m$^{-2}$ to 2.75 g C m$^{-2}$. At Klingenberg, the correlation and accuracy of the simulations have not improved by forcing the model with site specific phenology.

The improved correlation and accuracy at Lonzée in 2005 are mainly due a better representation of the fluxes after crop harvest. In 'JULES (crop-seasonal)', the LAI, crop height and rooting depth are equal to zero after crop harvest. As a result, the simulated photosynthesis and transpiration rates become zero.

The lack of improvement of the simulations with 'JULES (crop-seasonal)' at Klingenberg might be explained by the strong bias in soil moisture content between observed and simulated values (see Fig. B.1). As mentioned in Section 2.1, the soil moisture content has a strong impact on vegetation and land surface processes, like photosynthesis and evapotranspiration. It can be seen that the RMSE of the simulated soil moisture content at Klingenberg is much larger than the standard deviation of the observed values. Such values of RMSE are much larger than the one observed, for instance, at Lonzée in 2005 and could explain the difference in model performance between the two sites.

From this experiment, we can conclude that forcing the model with observed phenology improves the accuracy and the seasonality of the simulated fluxes, but the performance remains poor in case of large biases in soil moisture content.

### 4.5. Dynamic crop growth structure within JULES: evaluation of JULES-SUCROS

The simulations with JULES-SUCROS have been tested against the FLUXNET measurements to evaluate the realism of simulated dynamic growth and development processes to represent the current crop structure, phenology and production.

Fig. 2 shows that JULES-SUCROS yields better correlation with observed GPP and sensible heat flux than 'JULES (crop)'. The value of $r$ for the sensible heat flux has increased by 12.5%, and for the GPP by 10% (significance level $p < 0.15$). The correlation between measured and simulated latent heat flux has only improved by less than 5%. The value of $r$ for the soil moisture content has however slightly decreased. The overall accuracy of the simulations has improved as well. The RMSE of the latent heat flux, sensible heat flux and GPP have decreased by respectively 35%, 29% and 21%.

Fig. 3 shows that, compared to 'JULES (crop)', the accuracy of the simulated latent heat flux, sensible heat flux and GPP has increased at almost all FLUXNET sites. Besides this, the errors tend to be smaller than the standard deviations measured during the different growing seasons. This is however not the case at Klingenberg, where the error in soil moisture content is still large. On average, the RMSE of the soil moisture content at the different FLUXNET sites are similar or larger than the standard deviations observed at these sites, except at Lonzée in 2005 and Grignon in 2006. It can be seen that large biases in moisture content leads to large biases in fluxes.

Compared to the simulations with 'JULES (crop-seasonal)', the simulations with JULES-SUCROS achieve the same or even better correlations with the observed values (see Fig. 4). The same is valid for the accuracy of the simulations (Fig. 3). Fig. 5 shows that the monthly errors between measured and simulated GPP at the different FLUXNET sites have strongly decreased after crop harvest. Including dynamic crop growth and development within the land surface model has strongly improved the correlation and the accuracy of the simulations. In JULES-SUCROS, the seasonality of the simulated fluxes is consistent with the observations. This is not the case for the simulations with 'JULES (grass)' and 'JULES (crop)'.

The sowing and harvest dates simulated with JULES-SUCROS are on average consistent with the observed dates (see Table 2). The above-ground biomass differs by less than 15% from the observed values. The total above-ground biomass and yield at Lonzée in 2005 were around 1775 g DM m$^{-2}$ and 880 g DM m$^{-2}$. The simulated values are respectively 1515 g DM m$^{-2}$ and 575 g DM m$^{-2}$. The simulated crop is harvested 24 days earlier than what has been observed in reality. The fact that the crop develops its storage organs at the end of the growing season explains the relatively larger bias between measured and simulated yield compared to the bias in the above-ground biomass. This highlights the consistency and the realism of the simulated dynamic growth and development processes within JULES-SUCROS.

From this section as well as previous sections, it can be inferred that including a crop phenology strongly improves the accuracy of the simulation, at the condition that the soil hydrology is well parameterised. As mentioned in Section 2.1, the soil moisture plays an important role in many vegetation and land surface processes. However, it is quite difficult to correctly parameterise the soil hydraulic parameters for cropland. This is principally due the effect of management practices on soil structure that are very site specific and might vary during the growing season. In that respect, it is important to note that a "generic" parameterisation based on the literature values has been used in this study. The results obtained with JULES-SUCROS could certainly be further improved by fine tuning the soil moisture at each site.

In addition to the soil parameterisation, the discrepancies between simulated and observed values can be explained by the bias in length and timing of the simulated growing season. In JULES-SUCROS, the sowing and harvest dates depend primarily on the environmental conditions. The farmer may however decide to sow or harvest the crop at an earlier or later date for some other reasons. Next, JULES-SUCROS has been parameterised for a generic wheat crop and no model calibration has been performed.

Finally, part of the bias between measured and simulated fluxes might be explained by the energy imbalance of the measurements as discussed in Section 4.1. Although large improvements, the sum of the simulated latent and sensible heat fluxes still tends to overestimate the observed values. The MBE values for the simulated $\lambda E + H$ are +21.0 W m$^{-2}$, +25.8 W m$^{-2}$ and +12.0 W m$^{-2}$ at Lonzée in 2005, at Lonzée in 2007 and Gebesee in 2007, respectively. These values are very similar but opposite to the values mentioned in Section 3.3.1 regarding the underestimation of the observed $\lambda E + H$ compared to the observed available energy; *i.e.* −17.5 W m$^{-2}$, −24.1 W m$^{-2}$ and −10.8 W m$^{-2}$. This means that the overestima-

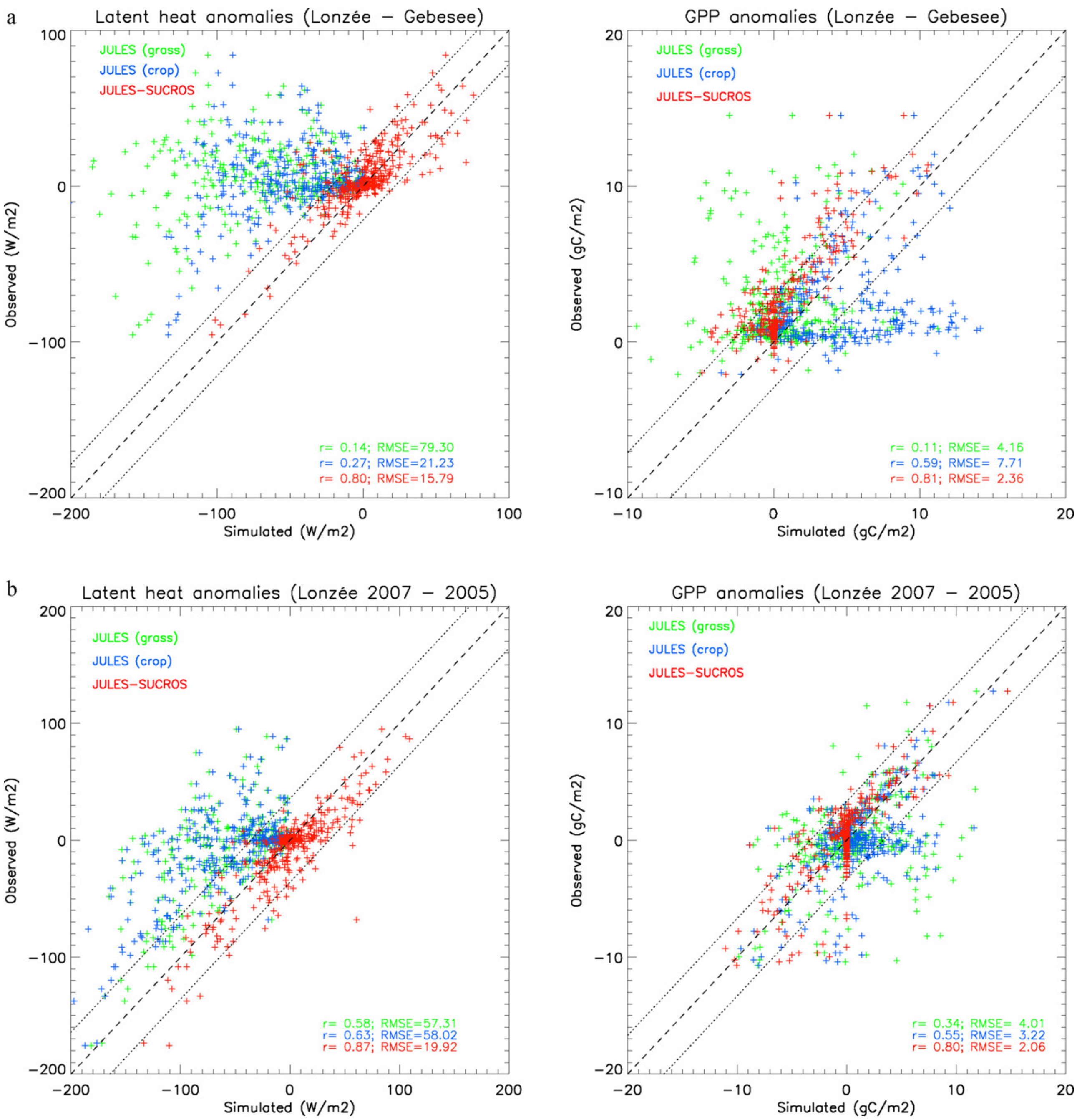


**Fig. 6.** Top row (a): correlation between observed and simulated anomalies of the latent heat flux and the GPP between Lonzée and Gebesee in 2007. Bottom row (b): correlation between observed and simulated anomalies of the latent heat flux and the GPP between the 2005 and 2007 growing seasons at Lonzée. The simulations have been performed with 'JULES (grass)' (green), 'JULES (crop)' (blue) and 'JULES-SUCROS' (red) for the different FLUXNET sites and growing seasons. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

tion of the simulated fluxes of sensible and latent heat could be due to the underestimation of the observed fluxes.

The results of this section indicate that a dynamic crop growth structure strongly improves the accuracy and the seasonality of the simulated fluxes. The dynamic growth and development processes within JULES-SUCROS consistently represent the current structure, phenology and production of the crop.

### *4.6. Inter-annual and spatial variability*

To evaluate the ability of the model to simulate the observed inter-annual and spatial variability of coupled water-carbon fluxes, the measured and simulated anomalies between different growing seasons have been compared. The growing seasons of 2005 and 2007 in Lonzée have been used to evaluate the sensitivity to inter-annual variability. The combination of the growings seasons of 2006 in Auradé, Grignon and Klingenberg and the combination of the growing seasons of 2007 in Lonzée, Gebesee and Lamasquère have been used to assess the sensitivity to spatial variability.

Fig. 6 shows the correlation between observed and simulated anomalies between two growing seasons. The variables represented are the latent heat flux and the GPP. Fig. 6(a) shows the anomalies between Gebesee and Lonzée in 2007, and Fig. 6(b) shows the anomalies between two different growing seasons at Lonzée.

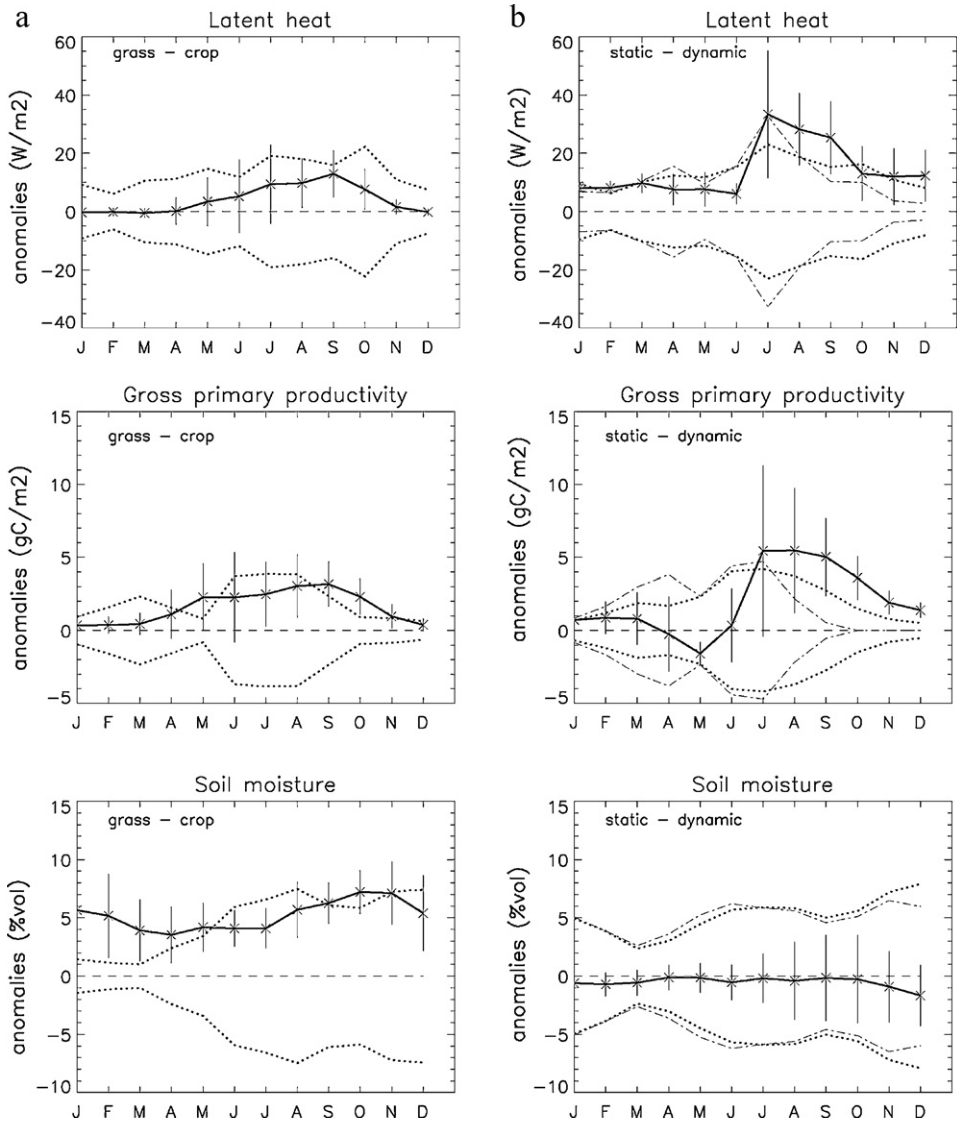


**Fig. 7.** Left panel (a): average anomalies (black line) of monthly latent heat flux, GPP and soil moisture content within the top 50 cm of the soil. The 95% interval of these anomalies over the different FLUXNET sites are represented by error bars. The dotted lines represent the 95% interval of the variations over sites and seasons in latent heat flux, gross primary productivity and soil moisture content simulated above a grassland. Right panel (b): same for a cropland with/without dynamic crop growth structure within the land surface model JULES. The dashed and dotted lines represent the 95% interval of the variations over sites and seasons in latent heat flux, gross primary productivity and soil moisture content simulated above respectively a cropland with/without dynamic crop growth structure.

The correlations are very poor for 'JULES (grass)' as the model is not able to capture the spatial and inter-annual variability of the fluxes above cropland. When using 'JULES (crop)', we observe a slight improvement of the correlation between the observed and simulated anomalies but it does not improve the accuracy of these anomalies. The RMSE of the simulated anomalies are, at best, similar to the standard deviations of the observed anomalies.

Finally, we see that JULES-SUCROS strongly improves the accuracy and the correlation (significance level $p < 0.05$) between the measured and simulated anomalies. The RMSE of the simulated anomalies are much smaller than the standard deviations of the observed anomalies. The RMSE of the anomalies in latent heat flux and GPP between Gebesee and Lonzé are respectively 15.8 W m$^{-2}$ and 2.4 g C m$^{-2}$, where the standard deviations are respectively 21.7 W m$^{-2}$ and 2.9 g C m$^{-2}$. The results were similar for the other combinations of growing seasons. The RMSE of the anomalies in latent heat flux and GPP between Lonzée 2005 and Lonzée 2007 are respectively 35.8 W m$^{-2}$ and 3.3 g C m$^{-2}$, where the standard deviations are respectively 19.9 W m$^{-2}$ and 2.1 g C m$^{-2}$. The values of the coefficient of determination are all larger than 0.80.

JULES-SUCROS appears to be very sensitive to inter-annual and spatial variability of the crop growth conditions over Europe. This could obviously be expected since JULES-SUCROS can really adapt to the local conditions, while in (standard) JULES, most of the vegetation properties are static and uniform. Sensitivity to inter-annual and spatial variability is a very important requirement for using this model for climate change and impact studies.

### 4.7. *Cropland versus grassland*

The sensitivity over Europe of the land surface model JULES to the land-cover type parameterisation, grassland versus cropland, has been evaluated by comparing the anomalies between 'JULES (crop)' and 'JULES (grass)' at the different FLUXNET sites located in different climatic regions in Europe.

Fig. 7(a) represents the average anomalies between a cropland and a grassland over the different FLUXNET sites and growing seasons for the simulated latent heat flux, GPP and the soil moisture content within the top 50 cm of the soil. It shows that the GPP and the latent heat flux on a grassland are on average larger than on a cropland. The differences between croplands and grasslands are mainly due to their difference in soil moisture content. Due to a lower infiltration rate (see Section 3.1), the soil of a cropland tends to contain less water. In addition to this, a cropland has on average a lower LAI compared to a grassland. By consequence, despite a higher rate of carboxylation, which enhances leaf photosynthesis and leaf conductance, crops tend to transpire and photosynthese less than grasses.

The anomalies between cropland and grassland vary from site to site within a range similar to the natural variations between the different sites. For the latent heat flux and the GPP, the anomalies and their variation are the largest during spring and summer (>10 W m$^{-2}$ and >3 g C m$^{-2}$, respectively). For the moisture content, the variations are the largest during the winter. These large variations can be explained by the fact that cropland and grassland are affected differently by the soil moisture regime at the different FLUXNET sites. Trade-off mechanisms create large uncertainties concerning the impact of cropland versus grassland on the land surface processes.

From these results, it can be concluded that the simulated land surface processes are sensitive to the difference in parameterisation between grassland and cropland. The sensitivity to these differences vary largely from site to site and depends strongly on the moisture regimes at the site.

### 4.8. Dynamic versus static crop

A first assessment of the impact of a dynamic crop growth structure on the simulated land surface processes over Europe has been made by comparing the anomalies between 'JULES (crop)' and

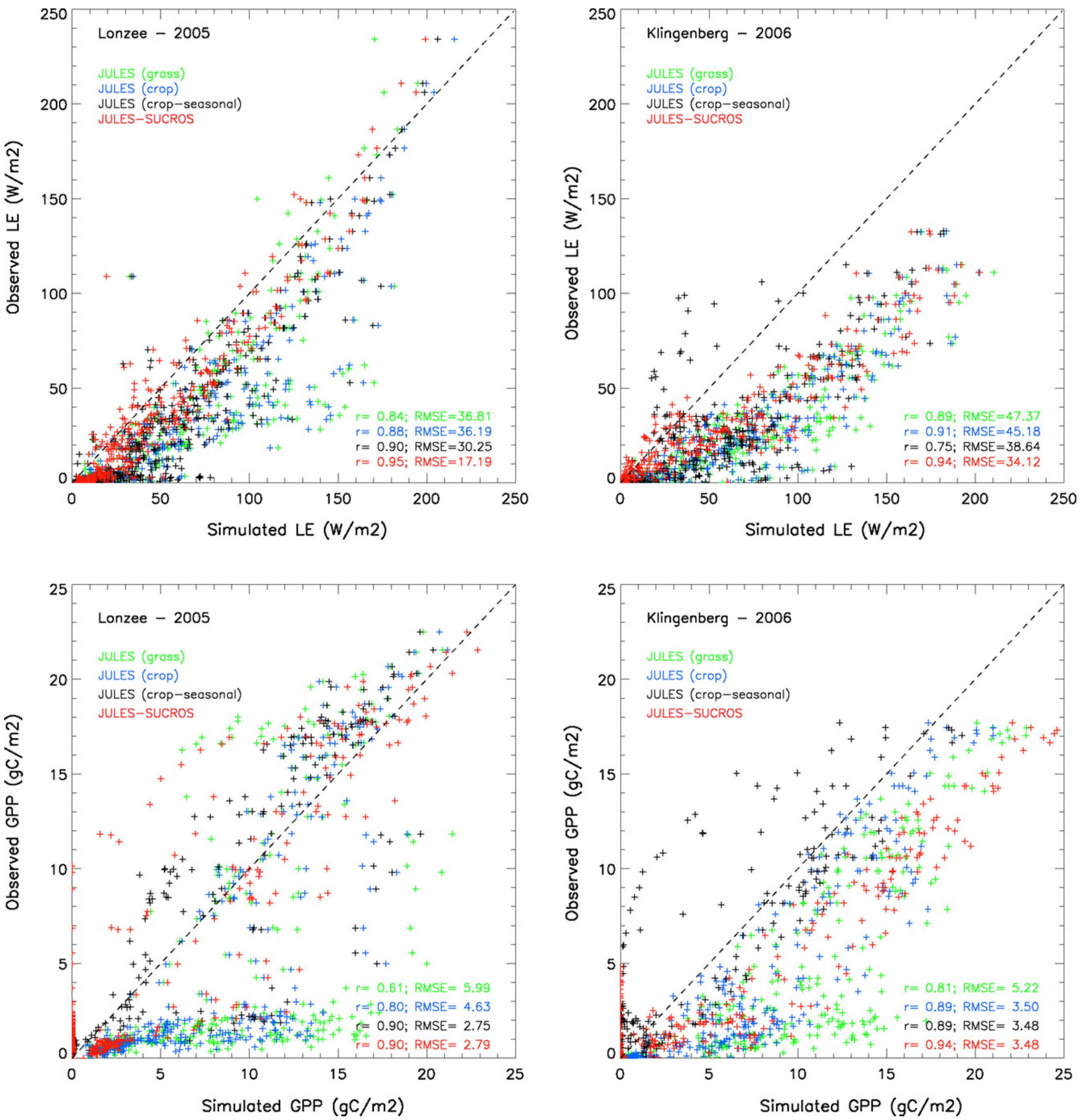


**Fig. A.1.** Correlation between observed and simulated daily latent heat fluxes and gross primary productivity for the growing season of 2005 at Lonzée and the growing season of 2006 at Klingenberg.

'JULES-SUCROS' at the different FLUXNET sites located in different climatic regions of Europe.

Fig. 7(b) represents the average anomalies between a dynamic and a static crop over the different FLUXNET sites and growing seasons. The anomalies of the latent heat flux and the GPP are on average quite large from June till October, when the dynamic cropland is bare after crop harvest. The range and the variations of these anomalies over the different FLUXNET sites are larger than the natural variations over these cropland sites. During the summer, these large variations can be explained by the difference in timing of crop harvest at the different FLUXNET sites. Later on, the differences between sites in terms of fluxes and soil moisture content anomalies are mainly due to the natural variations of the climate and soil moisture content, and their impact on the static crop.

The representation of the phenological cycle, growth, development and harvest of a crop has a large impact on the land surface processes during spring and summer. The range of the impact varies strongly from site to site since the dynamic crop is interactive and adapt to the local conditions, while the static crop does not.

## 5. Conclusions

In this paper, the development of a land surface model including a dynamic crop growth structure that fully fits within the biogeochemical modelling framework for natural vegetation has been described. This newly developed model, JULES-SUCROS, has been validated against measurements at 6 cropland FLUXNET sites in Europe. Subsequently, the performance of the model in representing the spatial and inter-annual variability over Europe has been assessed. Finally the sensitivity of the model to cropland versus grassland and to static versus dynamic crop has been evaluated.

From the results of this study, it can be concluded that the modifications of the land surface model JULES achieved by adapting the parameterisation for cropland and including a dynamic crop growth structure, have largely improved the land surface model performance over cropland. The simulated crop growth, energy and water fluxes are decidedly more accurate compared to the simulations with the original land surface model JULES. This is particularly significant given that the model has been paramaterised using standard literature values and not tuned to better match the observed values.

To respond consistently to a variety of environmental conditions, a process-based approach has been used to develop JULES-SUCROS. The results show that JULES-SUCROS simulates well the above-ground biomass. It captures both spatial and temporal variability of the growth conditions at the different FLUXNET sites located in three distinct climatic regions of Europe. It captures well the daily, seasonal and inter-annual variations in land surface processes. This is a prerequisite for using this model in climate change and impact studies over Europe.

The large biases between measured and simulated fluxes with the original JULES model highlight the importance of representing the interactive growth and development of crops to simulate properly the land surface processes on a cropland. Therefore, including a dynamic crop growth structure, such as JULES-SUCROS, within a GCM is likely to improve weather and climate simulations and thus help to better understand the interactions between crop growth, land and climate systems. Prior to this, some model calibration and a more precise soil hydraulic parameterisation might be required to further improve the model performance. In addition, the model has to be evaluated for other parts of the world and other prevalent types of cereals and crops in general, such as tubers or leaf vegetables.

Finally, we shall point out that the simulated fluxes are very sensitive to the differences in parameterisation between cropland and grassland. Substitution of natural grass with crops affects the simulated land surface processes, and might by consequence have an impact on the simulated climate. The sensitivity, however, varies from site to site. In addition, there are large uncertainties concerning the effect of land cover change, cropland versus grassland, on the land surface processes and the soil moisture content. Simulations with JULES-SUCROS have shown that the land surface processes are strongly affected by the vegetation dynamics. Therefore, including such a dynamic crop growth module within a GCM is expected to have an important impact on the simulated climate.

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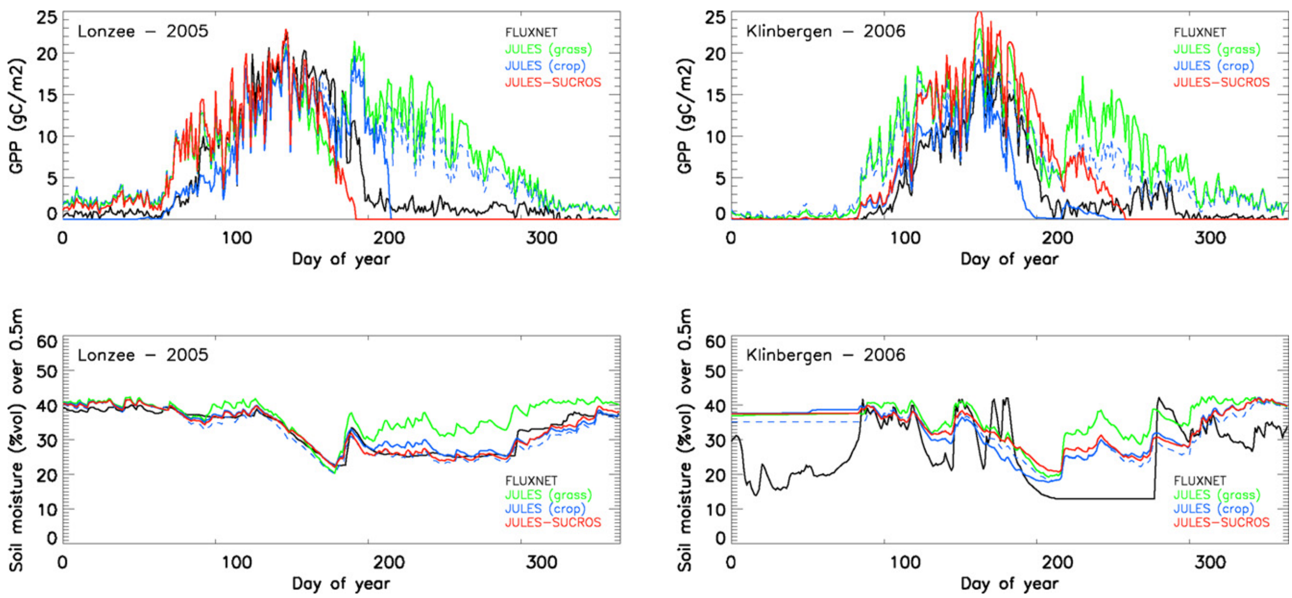


**Fig. B.1.** Time series of daily GPP and the percentage of moisture content within top 50 cm of the soil (missing measurements get the value 0) for the growing season of 2005 at Lonzée and the growing season of 2006 at Klingenberg.

## Appendix A. Correlation between simulated and observed daily variables at FLUXNET sites

In this section, we present site-specific results for the growing season of 2005 at Lonzée and the growing season of 2006 at Klingenberg. The plots show the correlation between observed and simulated daily latent heat flux and GPP. The simulations have been performed with 'JULES (grass)' (green), 'JULES (crop)' (blue), 'JULES (crop-seasonal)' (black) and JULES-SUCROS (red).

Fig. A.1.

## Appendix B. Times series of daily GPP and soil moisture at the FLUXNET sites

In this section, we present site-specific results for the growing season of 2005 at Lonzée and the growing season of 2006 at Klingenberg. The plots show the time series of the observed and simulated daily GPP and % soil moisture content within the top 50 cm of the soil. The simulations have been performed with 'JULES (grass)' (green), 'JULES (crop)' (dashed blue), 'JULES (crop-seasonal)' (plain blue) and JULES-SUCROS (red).

Fig. B.1.

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