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Importance of crop varieties and management practices: evaluation of a process-based model for simulating CO_2 and H_2O fluxes at five European maize (*Zea mays* L.) sites

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Abstract

Crop varieties and management practices such as planting and harvest dates, irrigation, and fertilization have important effects on the water and carbon fluxes over croplands, and lack or inaccuracy of this information may cause large uncertainties in hydraulic and carbon modeling. Yet the magnitude of uncertainties has not been investigated in detail. This paper provides a comprehensive assessment of the performances of a process-based ecosystem model called ORCHIDEE-STICS (a coupled model between generic ecosystem model ORCHIDEE and the crop growth model STICS), against eddy-covariance observations of CO_2 and H_2O fluxes at five European maize cultivation sites. The results show that ORCHIDEE-STICS has a good potential to simulate energy, water vapor and carbon dioxide fluxes from maize croplands on a daily basis. The model explains 23–75% of the observed daily net ecosystem exchange (NEE) variance at five sites, and 26–79% of the latent heat flux (LE) variance. Similarly, 34–83% of the variance in observed gross primary productivity (GPP) is accounted for by the model. However, only 3–81% of the variance of observed terrestrial ecosystem respiration (TER) is explained. Therefore, simulating TER is shown to be much more difficult than GPP. We conclude that structural deficiencies of the model in the determination of LAI and TER are the main sources of errors in simulating carbon dioxide and water vapor fluxes. A group of sensitivity analyses, by setting different crop variety, nitrogen fertilization, irrigation, and planting date, indicate that any of these factors is able to cause more than 15% change in simulated NEE although the response of these fluxes to management parameters is site-dependent. Varying management practice in the model is shown to affect not only the daily values of NEE and LE, but also the total seasonal cumulative values, and therefore the annual carbon and water budgets. However, LE is found to be less sensitive to management practices than NEE. Multi-site evaluation of the model and sensitivity analysis with respect to management practices performed in this research provide important insights on the model errors for estimating carbon and water vapor fluxes over European croplands.

1 Introduction

The global carbon budget has significantly changed due to the increase in the concentration of atmospheric CO_2 caused by various human activities. Agriculture, as a main way to produce food and feed, is one of these activities. In Europe, where they cover about one third of the continent area (i.e. 1.10 to 1.24 Mkm^2, FAOSTAT, 2003; Gervois et al., 2008), croplands are estimated to be a net source of CO_2 to the atmosphere (Vleeshouwers and Verhagen, 2002; Janssens et al., 2003; Ciais et al., 2010). In addition, the carbon dioxide flux over croplands contributes to the atmospheric CO_2 fluctuations at a seasonal scale and at an inter-annual scale (Smith et al., 2002; Freibauer et al., 2004). In order to monitor these fluxes, continuous micrometeorological measurements of the net exchange of carbon dioxide, water vapor and energy between various terrestrial ecosystems and the atmosphere have been developed worldwide using the eddy-covariance technique, since 1990's (Baldocchi et al., 2001; Baldocchi, 2003; Valentini, 2003). However, such point-scale flux measurements are difficult to scale up for quantifying regional carbon budgets due to spatial and temporal variations in climate, soil properties and management practices (Kucharik and Twine, 2007).

Soil-Vegetation-Atmosphere-Transfer (SVAT) models are powerful tools for quantifying the energy, H_2O and CO_2 exchanges between the terrestrial biosphere and the atmosphere. During the past few decades, numerous SVAT models have been developed worldwide. In Europe, ORCHIDEE (ORganising Carbon and Hydrology In Dynamic EcosystEms) is a widely used model for conducting continental carbon and water cycle research (Ciais et al., 2005; Piao et al., 2007). ORCHIDEE, initially designed based upon leaf and plant-scale physiological theories, is shown to perform well in simulating energy transfer, water vapor and carbon exchanges between vegetation and atmosphere at forest flux sites (Viovy, 1997; Ciais et al., 2005). At crop sites, ORCHIDEE is shown to be unable to capture the seasonal dynamics of fluxes (Krinner et al., 2005) due to the absence of a crop-specific phenology and management practices. Therefore, a specifically-designed crop growth model named STICS

(Simulateur mulTIdisciplinaire pour les Cultures Standard, Brisson et al., 1998; Brisson et al., 2002) has been coupled to ORCHIDEE. The ORCHIDEE-STICS coupled model (Gervois et al., 2004; De Noblet-Ducoudre et al., 2004) aims at estimating CO_2 and H_2O fluxes over croplands with a higher accuracy. At site scale, ORCHIDEE-STICS has been tested against flux measurements at two eddy covariance sites over winter wheat and maize in the USA (Gervois et al., 2004; De Noblet-Ducoudre et al., 2004). At these two US sites, ORCHIDEE-STICS model exhibits a satisfactory fit to the measured NEE and energy budget in a general manner, but its performance regarding different components of carbon fluxes has not been evaluated.

The net carbon exchange between atmosphere and terrestrial ecosystem depends not only on climate variables and soil properties, but also on management practices (Kucharik and Twine, 2007). Compared to forest and grasslands, croplands are more intensively managed, resulting in a complex and dynamic interrelation of physical, biological processes with human management decisions (Antle et al., 2001). More importantly, crop management practices, such as crop variety, planting date, fertilization, and irrigation are quite different across regions and change with time as well. Using an agro-ecosystem model to estimate the CO_2 and H_2O exchanges over croplands, large uncertainties may be expected because many of these management practices are poorly known. Although remote sensing may provide some information about crop N content (Bausch and Duke, 1996), crop water status (Jackson et al., 1981; Moran et al., 1994) and phenology (Viña et al., 2004), its accuracy is still not sufficient to meet the requirement of regional GPP estimation in temporal and/or spatial resolution in croplands (Reeves et al., 2005). Ecosystem models, mainly driven by meteorological variables and site-specific parameters, are widely used to conduct regional estimation of carbon and water vapor budgets (Andrew et al., 2005; Verma et al., 2005; Yan et al., 2007), but crop variety and agricultural management practice information are not well integrated into the model. A better understanding and accurate estimation, evaluation and analysis of the model uncertainties are necessary prior to regional or continental simulation.

The objectives of this paper are therefore: (1) to evaluate the performance of ORCHIDEE-STICS in modelling CO_2, H_2O fluxes and biometric variables over croplands at 5 selected maize sites in Europe; and (2) to quantify the uncertainties caused by different management drivers, in order to inform large scale integration studies.

2 Material and method

2.1 CarboEurope maize cultivation sites description

We consider five CarboEurope maize sites in three European countries (two sites in France, two sites in Netherlands and one in Germany). The geographical and agricultural information related to the studied sites is listed in Table 1. Soil properties (e.g. texture, field water capacity and wilting point), which are essential parameters of ORCHIDEE-STICS model, are measured or estimated at each site. At all sites, maize is grown for animal feed production in the study year. Variety, planting and harvest dates, fertilization and irrigation events are listed in Table 2. These data are used to develop the control simulation.

The Grignon (GRI) site is located about 40 km west of Paris, France. The crop rotation of the Grignon experiment includes maize, winter wheat, winter barley and mustard which is planted to serve as a catch crop to reduce nitrate leaching during winter. Dairy cow slurry is applied between the harvest of barley and the planting of mustard on 31 August 2004, and before maize sowing on 16 April 2008. Lamasquère (LAM) is located in south west of France. Previous cultivated crops are maize (2004) – triticale (2005) – maize (2006) – winter wheat (2007) – maize (2008) – winter wheat (2009). More detailed information on site characteristics and general information on soil and meteorology can be found in Béziat et al. (2009).

The sites Dijkgraaf (DIJ) and Langerak (LAN) are located in east and west of the Netherlands, respectively. Flux measurements started in 2007 at DIJ and in 2005 at LAN. The main cultivated crop is maize at both sites.

The site Klingenberg (KLI) is located in East of Germany. This site has been established in 2004. Cultivated crops include winter barley (2004), rapeseed (2005), and winter wheat (2006), maize (2007) and spring barley (2008).

Grown variety is different at each of these five sites. Planting dates differ by up to 25 days, ranging from 23 April (KLI) to 18 May (LAN) and the growing season length extends from 123 to 163 days. Amount of N fertilizer also varies from 65 kgN ha^{-1} (LAN) to 212 kgN ha^{-1} (DIJ). Irrigation (147.8 mm) is applied at LAM site only (Table 2).

2.2 Eddy covariance system and meteorological measurements

At each site an eddy covariance (EC) system is installed to measure the fluxes of CO_2, water vapor and sensible heat. The EC system consists of a fast response infrared gas analyzer (LI7500, LiCor, Lincoln, NE, USA) and a three-dimensional sonic anemometer (CSAT3, Compbell Scientific Inc, Logan, UT, USA). The system is a standard monitoring system used in the *Carboeurope* and *Fluxnet* networks (Dolman et al., 2006). Data are recorded with personal computer at a sampling frequency of 25 Hz for each channel. Average values are calculated and recorded at 30 min interval and used for analysis.

Meteorological measurements are made at each site on a half-hourly time step. Measured meteorological variables consiste of long- and short-wave radiation, air temperature, relative humidity, wind speed, precipitation, and mean near surface atmospheric pressure.

The flux time series are handled for checking for anomalous values arising from sensors malfunctioning caused in particular by interference of water condensation and rain drops with the optical path of the IRGA. NEE data associated with weak turbulence conditions are also rejected. Good quality data are then gap-filled using the CarboEurope-IP methodology (Reichstein et al., 2005; Papale et al., 2006a, b; Moffat et al., 2007; Béziat et al., 2009).

Net radiation, air temperature, and precipitation during the growing period at the five maize sites are shown in Fig. 1. The meteorological conditions are largely different among sites. DIJ and LAN sites have median precipitation (400–450 mm), and KLI is the wettest site (593.0 mm) during the growing season. The growing season precipitation at both GRI and LAM sites is quite low, with 152.7 mm and 169.4 mm, respectively. These two dry French sites have high solar net radiation (278.6 and 234.7 W m^{-2}) and high air temperature (19.6 and 17.2 °C), mirroring low precipitation. In contrast, the wettest KLI site in Germany is characterized by a cooler growing season air temperature of 14.4 °C.

2.3 Biometric measurements

At KLI site, leaf area index (LAI) and above ground biomass (AGB) are measured in a destructive manner. At other sites, LAI is measured on the basis of 30 randomly spatially distributed plants by means of a LiCor planimeter (LI3100, LiCor, Lincoln, NE, USA). LAI measurements are made based on two-weeks to 20-day interval. At harvest, 30 randomly spatially distributed plants are destructively collected and crop aboveground biomass including stem, leaf and ear (for grain maize) are measured using a balance (SPU 4001, OHAUS, Pine Brook, NJ, USA).

2.4 ORCHIDEE-STICS model

ORCHIDEE-STICS is a coupled model (Gervois et al., 2004; De Noblet-Ducoudre et al., 2004) between the generic global ecosystem model ORCHIDEE (Krinner et al., 2005) and the crop growth model STICS (Brisson et al., 1998, 2002, 2003). ORCHIDEE has robust physiological parameterizations to simulate energy-, hydrology- and carbon-related processes for diverse natural vegetation grouped into Plant Functional Type (PFT). ORCHIDEE has no explicit nitrogen cycle, while the supply of nitrogen is critically important to sustain growth and to achieve higher crop yield. In addition, crops have a very specific phenology which is not described by ORCHIDEE.

The STICS model developed for agronomical research is able to simulate crop growth processes for different crops and varieties (Brisson et al., 1998, 2002), but it is rather simple for handling ecosystem processes. Thus, in the coupled ORCHIDEE-STICS model, STICS is responsible for calculating LAI and crop height that are given on a daily time step to ORCHIDEE. STICS also accounts for management action information which is not available for ORCHIDEE, and consequently nitrogen and water stress can be alleviated by fertilization and irrigation. Alternatively, the model can automatically calculate fertilization and irrigation requirements and timing, based upon calculated optimal plant requirements (Brisson et al., 1998, 2002). When nitrogen or water become limiting for the plant development, a certain amount is applied daily until requirements are fulfilled. This "automatic management" option is used for investigating the model sensitivity to management practices (see Sect. 2.5).

Over Europe, ORCHIDEE-STICS was found to have some bias for simulating crop yields in some countries, especially for maize with a significant yield underestimation (Gervois et al., 2008). Smith et al. (2010) adjusted some parameters related to photosynthetic capacity (V_{cmax}) and environmental stress factors to apply the coupled ORCHIDEE-STICS model over a range of temporal and spatial scales in Europe. However, even after these adjustments, the model still underestimates the assimilation capacity and maize yields. The most likely reason is an inappropriate setting of the parameter for the maximal V_{cmax} (i.e. without any stress). In the first version of ORCHIDEE model (Krinner et al., 2005), the maximal V_{cmax} for maize is set as 39 $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ which is directly derived from Collatz (1992) universal model of C_4 photosynthesis. In the CLASS model, the V_{cmax} value is reported to be 54 $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ (Kothavala et al., 2005) and 62.5 ± 4.29 $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ in previous literature (Kim et al., 2007). The V_{cmax} value of maize determined from field measurements at the DIJ maize site is of 61.6–72.1 $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ (C. Jacobs, personal communication, 18 February 2009). In this study, we use the latest version of the coupled ORCHIDEE-STICS model, with prescribed maximal $V_{\mathrm{cmax}} = 100\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$.

Above ground biomass is estimated by ORCHIDEE as the sum of leaf, above ground sap and heart, and fruit carbon weighted by a conversion coefficient of carbon to biomass (Goudriaan et al., 2001).

2.5 Simulation set-up for model's sensitivities to crop varieties and management practices

In this section, we describe the ORCHIDEE-STICS model runs performed in order to assess model performance and sensitivity to management practices.

2.5.1 Control simulation

In the control experiment, on-site information on fertilization, irrigation, and planting dates is prescribed to ORCHIDEE-STICS. For crop variety, the version of STICS that we use includes 8 different maize varieties, each described by a set of parameter values, but none of these matches the exact variety planted on site. Thus, we select a moderate thermal requirement variety, FURIO, as the control variety by default (Lemaire et al., 1996).

2.5.2 Management practice simulations

For testing the model sensitivity to different crop varieties, two other sets of simulation with varieties with shorter (DK250) and longer (DK604) thermal requirements than FURIO are performed.

For the sensitivity to planting date, two scenarios are created, with planting prescribed 25 days earlier and later than the observed planting date, respectively. In order to guarantee the crop being matured for late planting simulation, the harvest date is set as 1 December. For early planting simulation, the harvest date is kept as observed.

For these sensitivity tests, we use the automatic management, instead of the "true" values prescribed at each site as in the control simulation. A summary of the simulation set-up for model sensitivities is listed in Table 3.

2.6 Taylor plot analysis

A Taylor diagram (Taylor, 2001) is used to examine the agreement between model and data and the model's sensitivities to crop varieties and management practice. Three statistical indicators, correlation coefficient (*R*), standard deviation (STD) normalized by observed STD (NSTD) and root mean square error (RMSE), are integrated into one single polar plot to display the relationship between the model and the data. On a Taylor diagram, the performance of model simulation is specified by a single point, the *R* value being the polar angle, and the NSTD the polar axis. The higher the *R* and the farther from 1 the NSTD, the better the agreement between model and data is. Similarly, when comparing two simulations that differ by a parameter value, the longer the distance between the two simulation points, the greater the sensitivity to that parameter.

3 Results and discussion

3.1 Comparison between simulated and measured biometric variables

Figure 2 compares the simulated LAI for control simulation and the observations at DIJ, GRI, KLI, LAM, and LAN sites. ORCHIDEE-STICS is able to produce a good agreement with observed LAI at DIJ, GRI, and LAN sites. At KLI site, the simulated LAI significantly lags the measurements about 7 to 10 days during the stage of quick increase of LAI (45–80 days after planting, DAP). The discrepancy between the simulated and the measured LAI during the late period can be partly explained by a hail storm (38 mm in 30 min) on 88 DAP (20 July 2007). Overall, one shortcoming of STICS is the underestimated peak LAI value at four out of the five sites (excluding DIJ site). STICS assumes that the crop is able to complete a specific phase of its development only once an cumulative temperature threshold is reached (Brisson et al., 1998, 2002). This oversimplified calculation of LAI development is a source of discrepancy between simulated and observed LAI. LAI calculation in STICS is also closely dependent on the water and nitrogen stresses. At the GRI and LAM sites, where growing seasonal temperature is high (17.2 and 19.6 °C, respectively) and growth period available water (precipitation plus irrigation) is low (169.4 mm and 300.5 mm, respectively), the model predicts lower LAI values compared to observations. High temperature definitely accelerates crop's phenology development and shortens the period of leaf biomass accumulation, and low precipitation exerts water stress on the development of LAI. In addition, our simulations do not consider organic fertilization in previous winter at LAM site. This may also explain the extremely low simulated LAI at LAM. Last, the modeled senescence phase (when LAI is decreasing before harvest) occurs too sharply, unlike in the measurements (Fig. 2).

Comparisons between simulated and observed above ground biomass (AGB) at harvest are shown in Fig. 3. ORCHIDEE-STICS produces acceptable estimations of AGB at DIJ and LAN sites, with error percentage (EP, defined as the ratio of the difference between the observed and modeled to the observed value) of 16% and −7%, respectively. However, large discrepancies are seen at LAM site, with error percentage of −47%. At the LAM site where LAI is extremely underestimated, AGB is consistently underestimated. Due to mismatch of LAI in early stage and hail storm damage in the middle of growth period, the model overestimates AGB at KLI site. The linear correlation coefficient between the average LAI bias (simulated LAI minus observed LAI) and AGB bias is 0.81, indicating that the AGB model error is mainly resulted from the error in LAI.

3.2 CO_2 and water vapor flux simulations

3.2.1 Seasonal variations of carbon fluxes

The dynamics of daily NEE and LE at the five maize sites are shown in Fig. 4. All model and data values are smoothed at 5-day running means to eliminate very high frequencies following Gervois et al. (2004) and De Noblet-Ducoudre et al. (2004). The

ORCHIDEE-STICS model has a good ability to reproduce seasonal variations of NEE over all sites. The coefficient of determination (R^2) between simulated and measured NEE are 0.73, 0.57, 0.23, 0.74, and 0.48 at DIJ, GRI, KLI, LAM, and LAN sites, respectively. Root mean square error (RMSE) for NEE at five sites are 0.55, 0.67, 1.63, 0.51, and 0.84 gC m^{-2} day^{-1}, which is much higher than in the ORCHIDEE comparison at selected FLUXNET sites (Chevallier et al., 2006). For GPP, the model is able to explain 68, 72, 34, 83 and 32% of the variance, with RMSE values of 0.79, 0.56, 1.65, 0.45, 1.06 gC m^{-2} day^{-1}; against only 9, 74, 41, 81, and 3% for TER, with RMSE values of 2.53, 0.69, 1.50, 0.59, and 1.19 gC m^{-2} day^{-1}. Among the five maize sites, the maximum of observed NEE reaches −15 gC m^{-2} day^{-1}. Controlled by different climatic conditions and crop development, the timing of peak uptake of NEE differs between sites. ORCHIDEE-STICS captures the amplitude and the timing of NEE peak uptake at the GRI and LAM sites, and to a lesser extent at DIJ, and LAN. However, visible mismatch appears at KLI site, especially in the mid-late period, which results from a hail storm (38 mm in 30 min) on 88 DAP (20 July 2007) that partly damaged maize plants. By splitting the growing season to pre- and post-hail storm periods, R^2 values are 0.75 vs. 0.03, and RMSE are 1.8 vs. 5.3 gC m^{-2} day^{-1} for NEE. For LE, R^2 is slightly improved from 0.45 to 0.62, but RMSE also increased from 15.7 to 26.5 W m^{-2} in pre- and post-hail storm.

During the early crop growth period (from planting date to 45 DAP), TER is slightly larger than or comparable with GPP. Therefore, crop field tends to be a small source or carbon neutral, while air temperature remains relatively low in all sites at that period. At three out of the five sites (GRI, KLI and LAM), these observed NEE trends are well captured by the model. At the two other sites (DIJ and LAN), the observed NEE values during the early crop growth fluctuate between 0 and 5 gC m^{-2} day^{-1}, while the average differences between the simulated and observed NEE are −2.22 and −0.46 gC m^{-2} day^{-1}, respectively. This suggests that other factors such as crop history and/or soil tillage that are not described in ORCHIDEE-STICS also affect TER and consequently NEE (Aubinet et al., 2009).

During the middle crop growth period (from 46 DAP to 115 DAP), all maize fields act as obvious carbon sinks, with GPP exceeding TER. The magnitude of this sink depends not only on meteorological variables but also on available soil moisture. At the LAM site, high solar radiation and high temperatures accompanied by low precipitation (152.7 mm) and amount of irrigation (150 mm) lead to high GPP, and the observed TER is high as well. As a consequence, NEE tends to be very low. At the GRI site, crop growth period precipitation is also low (170 mm), but solar radiation and air temperature remain moderate. Therefore, the interactive effects of radiation, temperature and precipitation do not significantly suppress NEE uptake, unlike observed at the LAM site. The ORCHIDEE-STICS model reproduces these variations of NEE in the middle crop growth period well, but discrepancies exist at the KLI site.

During the late growth period (after 115 DAP), the observed NEE uptake weakens due to plant senescence. The simulated NEE uptake is obviously overestimated at DIJ, KLI, and LAN. The cause of this overestimation can be attributed to an overestimation of LAI by STICS (Fig. 2). The observed LAI keeps its peak value for only about 2 weeks, and then slowly decreases towards zero. Oppositely, the simulated LAI remains at its maximum during four weeks, and then drops to 0 at the harvest date. This mismatch of LAI during the late growth period substantially affects the model's performance for NEE, especially at those sites where the growing season temperature is relatively low, for example the KLI (average temperature 14.4 °C) and DIJ (average temperature 15.8 °C) sites. The decline in LAI of crops in the late growing periods is mainly due to plant senescence. However, lower temperatures at these sites can not satisfy the requirement of model's specified GDD to complete physiological maturity in the observed growing period, and the plant is forced to mature by the prescribed harvest date.

3.2.2 Seasonal variations of latent heat flux

At the GRI and LAM sites, both simulated and observed LE present seasonal variations. At the three other sites, however, LE does not show apparent seasonal variations, but fluctuates between 0 and 120 W m^{-2}. The lack of a trend in seasonal LE measured at these sites may come from frequent precipitation (total precipitation during growing season with 452, 593, and 403 mm, respectively), low net radiation (mean net radiation with 190, 228, and 215 W m^{-2}, respectively), and associated high relative humidity (75.4, 75.8, and 80.1%, respectively). ORCHIDEE-STICS is generally able to capture the LE differences between sites. Overall, ORCHIDEE-STICS is able to explain 33, 65, 43, 79 and 29% of the observed variance, respectively, and the RMSE values at five sites are 1.28, 0.61, 1.07, 0.50, and 0.96 W m^{-2}, respectively. The discrepancy between simulated and measured latent heat fluxes can be partly explained by imbalanced energy budget with eddy covariance technique (Wilson et al., 2002; Li and Yu, 2007), because the model always assumes energy balance while the measured energy components are not forced to balance in this research.

3.2.3 Overall evaluation of ORCHIDEE-STICS

The overall model performance in simulating the seasonal variations of NEE, LE, TER, and GPP is summarized with a normalized Taylor plot (Taylor, 2001) in Fig. 5. Among all subplots, normalized standard deviation (STD), root mean square error difference (RMSD), and correlation coefficient (*R*) for observations are always 1, 0, and 1, respectively. Correlation coefficient for GPP is high around 0.9 except at the KLI and LAN sites with *R* values slightly lower than 0.7. For TER simulations, *R* values are low at sites like DIJ and LAN in the Netherlands (0.29 and 0.18). For NEE, high correlation coefficients are obtained between the simulated and the observed values at four out of five sites. Similar to the model's good performances for GPP and NEE, the simulation results of LE also give high *R* values of 0.58, 0.81, 0.66, 0.89, and 0.54, respectively.

3.2.4 Seasonal budgets

Figure 6 shows the comparisons between simulated and observed seasonally cumulative NEE, LE, GPP, and TER since planting date. One can see that the simulated cumulative NEE is in good agreement with the observed values at GRI and LAM sites, with EP values of 2.0% and 1.3%. However, a large discrepancy exists between the simulation and the observation at the three other sites, simulated cumulative NEE being over-estimated (i.e. more uptake). The EP values are 49%, 125%, and even 377% at the DIJ, LAN, and KLI sites, respectively. Majority of the cumulative NEE bias may result from overestimation of GPP and originally from LAI during the late crop growth, as seen above. At GRI and LAM sites, the seasonal NEE budget is well simulated because of roughly equivalently underestimated simulated GPP and TER (Fig. 6). At DIJ, KLI, and LAN site, where the simulated seasonal NEE budget is remarkably overestimated, the main bias resulting from the estimation of GPP or TER or both.

For cumulative LE, the model presents good (EP = 2.4%, 0.3%, 2.4% and −13%) results compared to observation at four out of five sites. The unrealistic LE simulation at the KLI site (EP = 64%) may be due to the damage caused by hail storm in the study year.

The model reproduces an acceptable cumulative GPP at DIJ, GRI, and LAN sites, with EP values less than 15%, but overestimates GPP at KLI and LAN sites (EP = 58%) and underestimates at LAM (EP = −32%) (Fig. 5). Model's performance for GPP is closely related to the one for LAI (Suyker et al., 2004; Xu and Baldocchi, 2004). Overall, model bias exhibited for GPP looks similar to the one for AGB (comparing Figs. 3 and 5).

For cumulative TER, the model has rather poor performances at all sites. The EP values are 31%, 23%, 20%, 50%, and 52% at the five sites, respectively. This indicates that the processes controlling cumulative TER in ORCHIDEE are far from perfect, e.g. no vertical distribution of soil C pools, soil C initialization bias caused by unknown site and disturbance history. Currently, TER is considered as the sum of heterotrophic and autotrophic respirations (Krinner et al., 2005). Part of the model-data mismatch for TER at LAM and LAN may certainly be explained by a GPP bias (see Fig. 5). On the other hand, at DIJ and KLI where NEE right after planting is underestimated (see Fig. 4), most of the model error should be related to heterotrophic respiration simulation since no autotrophic respiration was involved in this period. The heterotrophic respiration in the model assumes that that the ecosystem carbon balance is in steady-state equilibrium, but this hypothesis may not be true in reality (Carvailhais et al., 2008), especially for agroecosystems where the soil is commonly disturbed by various human activities.

3.3 Water use efficiency

The crop water use efficiency (WUE, $\mathrm{gC\,mm^{-1}H_2O}$) is defined as the ratio of daily GPP to daily ET. The comparison between simulated and observed daily WUE at the 5 maize cultivation sites is shown in Fig. 7. Generally, the WUE is relatively low in the beginning of the growing season and immediately after harvest. The higher values of WUE occur during the peak of the growing season when crop LAI approaches or stays at its maximum. During this peak crop growth period, the WUE of maize is observed to reach 8–15 $\mathrm{gC\,mm^{-1}H_2O}$. Comparison between the simulated and observed WUE shows a linear relationship at the 5 sites. The model was able to explain 51, 31, 23, 57, 31% of the variance in observed WUE at DIJ, GRI, KLI, LAM, and LAN, respectively. Although the correlation coefficients between the simulated WUE and the measured WUE are low, the majority of the measured WUE values were within the 3σ confidence limits of the linear regression. Another possible source of errors for the simulated WUE may originate from the energy imbalance problem of eddy covariance technique because energy budget has important effect on WUE (Li and Yu, 2007).

3.4 Sensitivity of modeled fluxes to management practice

3.4.1 Seasonal variations

We select NEE and LE as two representative fluxes related to carbon and water balance of agroecosystem. Figure 8 shows the Taylor plot (Taylor, 2001) for the response of NEE to different sensitivity tests on varieties, fertilization, irrigation, and planting date.

From Fig. 8, we find that NEE responds sensitively to crop varieties at three sites (KLI, LAM, and LAN). However, at the other two sites (DIJ and GRI), NEE is only weakly sensitive to that parameter. We assume that it is the difference in climate that modulates the sensitivity to crop varieties among sites. In the STICS model, varieties are described by different growing degrees day (GDD) thresholds, so that the air temperature during the early growth period determines the sensitivity of simulated NEE to crop varieties.

Regarding fertilization, at LAN site where fertilization is applied at a low rate (65 kgN ha^{-1}), a large sensitivity of NEE is found when automatic fertilization is given by STICS, instead of the prescribed observed values. At sites with moderate fertilization (LAM and KLI with 84 kgN ha^{-1} and 91 kgN ha^{-1}, respectively), the model shows weaker sensitivities than at sites with low fertilization rate. However, at sites with high fertilization rates (DIJ and GRI with 212 and 140 kgN ha^{-1}, respectively), the NEE sensitivity is very small (Fig. 8). The response of the simulated NEE to irrigation has large difference among five sites. The change in the statistical indices (STD, RMSD, and R) is very large at GRI, a dry site (Fig. 8). However, this response is weaker at the DIJ site. Such inter-site differences in the NEE sensitivity to irrigation can be explained by differences in the total amount of available water in soil profile during the crop growth period. The total growing season precipitation at KLI and DIJ are 593.0 mm and 452.5 mm, respectively. In contrast at the dryer site GRI, the growing season precipitation is only 169.4 mm and no additional water is supplied by irrigation. At another low-precipitation site, LAM, the growing season precipitation is only 152.7 mm, but 147.8 mm irrigation is applied during the growing period. Therefore, the response of NEE to irrigation at LAM shows a weaker sensitivity than at GRI. Thus, for both fertilization and irrigation, the differences between actual amounts and optimal crop requirements determine NEE responses.

Figure 8 illustrates the sensitivity of simulated NEE to planting date. This management parameter greatly affects the simulated NEE. A planting date shifted by 25 days causes a very remarkable change in simulated NEE over all the sites. The change is mainly reflected as a form of decreased R and increased STD in the Taylor diagram. The reason of this is that in the "control" simulation, crop development has generally already benefited of several GDD during the 25 first days after planting. In the "late planting" simulation, crop development cannot account for these GDD which causes a large phase lag compared to the "control" simulation. In contrast, planting the seeds 25 days earlier than in the "control" experiment induces a shorter phase lag, because generally few GDD are accumulated in this early 25-day period.

Figure 9 shows the sensitivity of LE to crop management practice parameters. There is no large change (see the length of the arrow) in statistics for the responses of LE to varieties and fertilization at most sites, contrary to what is obtained for NEE. Only a weak sensitivity is found for the responses of LE to varieties (LAM) and fertilization (LAN). At the dry sites GRI and LAM where the available water (precipitation plus irrigation) is low, significant sensitivity of LE to irrigation is found. Otherwise, the automatic model irrigation amounts given by STICS do not induce any significant change in LE because of the difference in available water between prescribed and model automatic irrigation amounts is very small. Compared to crop varieties, fertilization, and irrigation, planting date is a remarkably sensitive parameter in determining LE, as for NEE. A later planting date causes a greater change in simulated LE.

Sensitivity of the fluxes (NEE and LE) to crop variety and management practice at all maize sites is shown in Fig. 10. Box plot with median and interquartile values show that all statistical indicators, normalized STD, RMSE, and R, vary largely for all maize sites. Normalized STD varies from 0.7 to 2.0, and normalized RMSE fluctuates between 0.3 and 2.0 for NEE. The median values of the normalized STD and RMSE for NEE are also deviated away from 1. However, normalized STD and RMSE for LE are located in relatively narrow range and the median values of normalized STD and RMSE are at or near 1, implying that the simulated LE is less sensitive than NEE.

3.4.2 Seasonal budgets

In order to test the sensitivity of cumulative fluxes to management parameters, a sensitivity index (SI) is defined as the ratio of the difference between cumulative simulated and measured fluxes to the cumulative measured flux (Fig. 11). It is found that the SI can vary with crop varieties and management practices, but the sensitivity to a specific variable is site-dependent. It is evident that the magnitude of SI is closely related to the difference between the observed and the model-automatically assigned values for fertilization and irrigation. If the difference is large, the value of SI is large as well. For example, at the driest GRI site (with 169.4 mm precipitation and no irrigation) the NEE shows a largest SI for irrigation. At the lowest nitrogen application rate LAN (65 kgN ha^{-1}) site, the simulated cumulative NEE has a significant sensitivity to fertilization. For the sensitivity of the cumulative NEE to crop varieties, at the LAM and LAN sites, SI values are larger than 15%. For planting date simulations, the SI shows a value larger than 15% at LAM site for late planting and LAN site for early planting; while all the SI values are lower than 15% at the three other sites. In this respect, it is found that the annual NEE is much less sensitive to planting date than the seasonal NEE variation. By contrast, the sensitivity of annual NEE to other management parameters is similar to the one of seasonal NEE. This finding suggests that a shift in planting date strongly impacts the phase of the NEE while the other drivers have a stronger control on its amplitude.

Compared to seasonally cumulative NEE, LE is found to be less sensitive to crop varieties and nitrogen applications (Fig. 11) at all five sites, where all SI values are less than 15%. The model presents large response of LE to irrigation with a larger than 15% of SI at KLI site only. Early planting with 25 days causes large LE responses at DIJ, KLI and LAN sites, while late planting with 25 days produces negative effects on cumulative LE at three out of five sites (KLI, LAM and LAN).

4 Discussion

Compared to other terrestrial systems, agricultural ecosystems are more complicated and highly affected and managed by human beings. Water and carbon fluxes in agroecosystems are commonly affected by various management practices. Some recent ecosystem models are capable of taking into account for the effects of management practices. Although these ecosystem models are far from perfect, they are still widely used in ecosystem research. However, ecosystem models must be intensively evaluated against in situ measurements and their sensitivities to those management factors with large spatial variations must be investigated before applying at the whole European croplands.

In this paper, by evaluating ORCHIDEE-STICS model at five maize sites over Europe, it is found that the model's performance differ across sites, and for the different output variables (e.g. GPP, TER, NEE or LE) even at one specific site. At the sites where LE and GPP are poorly modeled, the main reason of the model-data mismatch is the phase-lag in STICS-simulated LAI. Therefore, improving the LAI seasonal dynamic in future version of ORCHIDEE-STICS should potentially improve the performance in simulating GPP and LE because both are highly dependent of LAI as documented by Suyker et al. (2004) and Xu and Baldocchi (2004). TER in ORCHIDEE-STICS model is simulated as the sum of autotrophic and heterotrophic respirations. Autotrophic respiration is strongly depended on plant biomass and temperature, while heterotrophic respiration is related to soil temperature, soil moisture and soil carbon pools. Simulation of autotrophic respiration is well understood (Ruimy et al., 1996), however, quantifying heterotrophic respiration comprised large of uncertainties (Trumbore, 2006). In the current version of ORCHIDEE, two bucket layers (ground and below ground) are considered for soil moisture and several layers (prescribed by user) for soil temperature. As other land surface models, the accuracy of soil moisture is not good enough. The deficiency of modeled soil temperature and moisture may be part of the reason of the disagreements between the measured and the simulated TER. At the sites where

GPP and LE are well simulated but TER and NEE are poorly captured, apart from the errors from soil temperature, moisture and carbon pools, the steady-state hypothesis in the model construction is also a most likely reason. Each simulation is initially set at steady state, while, in reality, agroecosystem is intensively affected by various human activities, for example ploughing, crop rotation, fertilization and irrigation, which all have the potential for disturbing the assumed steady state (Aubinet et al., 2009). Therefore, taking into account for previous cropping or land-use history in future simulations will certainly improve the model's performance in TER and hence NEE simulations, by replacing steady-state carbon stocks with observed stocks.

Maize, being a thermophilous crop, is widely cultivated in Europe but mainly distributed over the region bounded by 40° N–55° N in latitude and 9.5° W–19.5° E in longitude (Gervois et al., 2008). Over this maize grown area (defined as maize exceeding 5% of the total land area), total annual precipitation ranges from 500 to 1400 mm, and annual mean temperature varies from 6 to 17 °C. At the five studied sites, total annual precipitation fluctuates between 460 and 970 mm and mean annual temperature varies from 8.5 to 13.5 °C during the simulated year. Thus, four of these sites are very well representative of the climate range where maize is grown in Europe. However, precipitation is frequently not able to satisfy the water-demand in maize growing period and threatened maize production. Irrigation, therefore, is applied to guarantee crop yield in some areas such as LAM site. In this study, nitrogen application and precipitation ranges have reasonable and large gradients. Planting date has 25-day difference among five sites and we also conduct more simulations with actual planting date ±25 days at each site for potentially spatial extension of our results. The representativeness of climatic conditions and the reasonability of the setting of management practice are properly able to extend the suitability of our results to a largely spatial extent over European maize grown area. The lack of the information about crop varieties and management practices may not produce very significant change in LE but may cause large uncertainties for carbon fluxes over European croplands. In order to enhance the model's performance, further improvement in the calculation of LAI and

TER might also be expected. Another potential way to improve model's performance in carbon and hydrology simulations would be to assimilate the remotely sensed LAI, soil moisture and/or soil temperature into ORCHIDEE-STICS model based on modern data assimilation techniques, such as ensemble Kalman filter and Bayesian inversion. These combined efforts might have great potentials to accurately quantify the carbon and water vapor fluxes over regional integration.

5 Conclusions

This paper evaluates the performance of the ORCHIDEE-STICS model against carbon and water fluxes data at five maize eddy-covariance sites from the CarboEurope project. The results suggest that the coupled model is able to capture the seasonal dynamics of NEE and LE. However, at sites with low air temperature during crop growing period, the model presents phase lags of 7 to 10 days in LAI compared to the observations. This mismatch might explain the errors of simulated GPP and LE. Overall, ORCHIDEE-STICS explains highly more than 70% of the variances (R^2) of any observed daily component of the carbon budget or latent heat flux at DIJ and LAM, moderately around 50% of the variances of the observations at GRI and LAN, and poorly lower than 30% of the observations at KLI site. Among four variables of our interests, cumulative total GPP during crop growing season is satisfactorily reproduced by the model. However, the seasonal total TER over all sites is markedly underestimated and hence obvious overestimation in seasonal total NEE is derived. For total transpirational water, the agreement between the measurement and the simulated is acceptable as well.

Sensitivity analysis by means of setting several different cases related to crop variety, fertilization, irrigation and planting date, shows that any of considered factors is able to cause large changes in the simulated NEE and LE. Nevertheless, the sensitivity of LE to the changes in these management practices is lower than that of NEE. The variations of management practices affect not only the daily NEE and LE but also the total seasonal cumulative values, these later changes being much more site-dependent. For irrigation and fertilization changes, the magnitude of the response of specific management practice on NEE and LE strongly depends on the difference between the prescribed and automated water or nitrogen supplies.

Multi-site evaluations of the model's performance and sensitive analysis performed in this study identify the potential model weaknesses and will be also helpful to further improve the model structures and ecophysiological processes. This study provides a clear envision on the accuracy and uncertainties of model estimates of carbon and water vapor flux at European scale.

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Table 1. Geographic information and cropping year for five European maize sites.

Abbreviation	Full name	Country	Longitude	Latitude	Year
DIJ	Dijkgraaf	Netherlands	5°38′ E	51°59′ N	2007
GRI	Grignon	France	1°58′ E	48°51′ N	2005
KLI	Klingenberg	Germany	13°1′ E	50°53′ N	2007
LAM	Lamasquère	France	1°24′ E	43°50′ N	2006
LAN	Langerak	Netherlands	6°21′ E	53°24′ N	2005

Table 2. Crop variety, planting/harvest date, fertilization and irrigation.

Site	Variety	Planting	Harvest	Nitrogen fertilization	Irrigation
DIJ	La Fortuna	4 May	27 September	212 kg ha^{-1}	0 mm
GRI	Anjou 288	9 May	28 September	140 kg ha^{-1}	0 mm
KLI	Rosalie*	23 April	2 October	84 kg ha^{-1}	0 mm
LAM	Goldaste	1 May	31 August	91 kg ha^{-1}	147.8 mm
LAN	La Fortuna	18 May	19 October	65 kg ha^{-1}	0 mm

The symbol * indicates unknown crop variety, and recommended variety is used.

Table 3. A summary of the simulation set-up for model's sensitivities.

Simulation	Variety	Fertilization	Irrigation	Planting date
Control simulation	FURIO	Observed	Observed	Observed
Variety sensitivity 1	DK250	Observed	Observed	Observed
Variety sensitivity 2	DK604	Observed	Observed	Observed
Fertilization sensitivity	FURIO	Model calculated	Observed	Observed
Irrigation sensitivity	FURIO	Observed	Model calculated	Observed
Early planting sensitivity	FURIO	Observed	Observed	Observed−25
Late planting sensitivity	FURIO	Observed	Observed	Observed+25

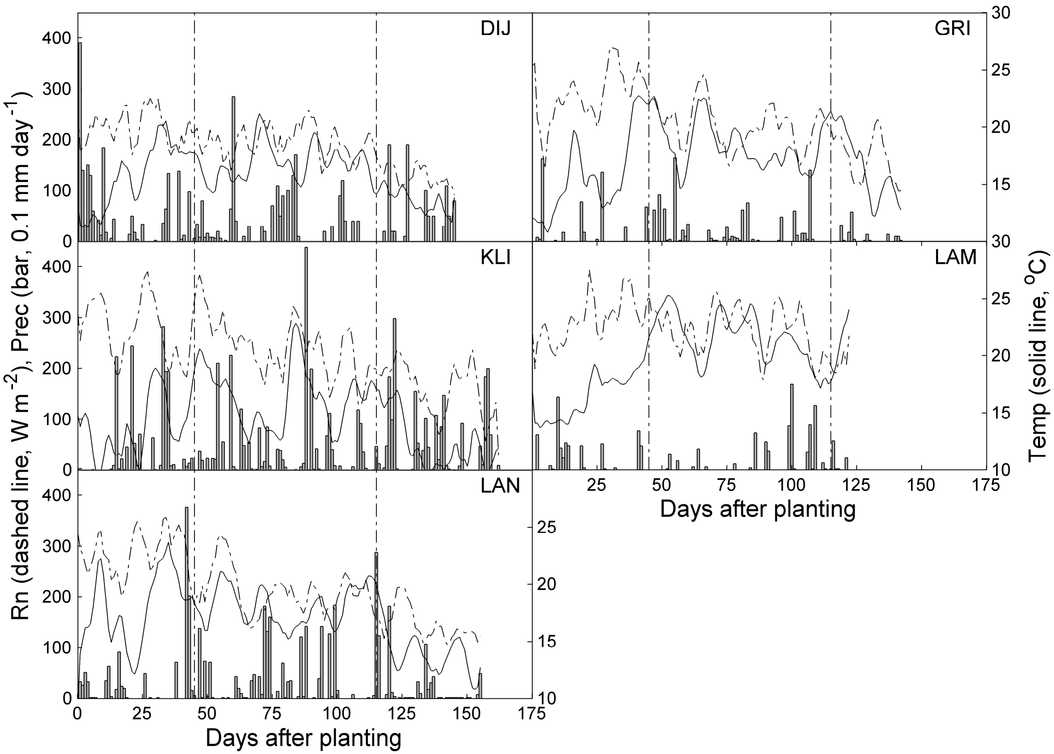

Fig. 1. Net radiation (Rn, dashed line), temperature (Temp, solid line), and precipitation (Prec, gray bar) during the growing season at 5 maize sites. Rn and Temp are smoothed for 5 days and Prec is shown on daily basis. The first vertical dashed line x = 45 is defined as the end of the early crop growth period, and x = 115 is defined as the start of the late crop growth period. Between the two lines, it is defined as the middle crop growth period.

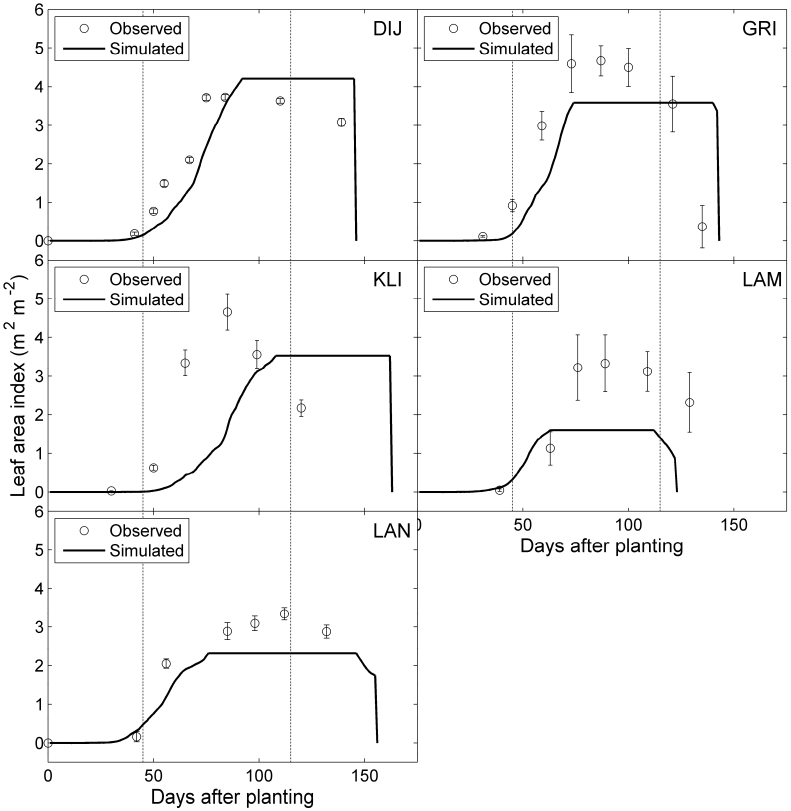

Fig. 2. Simulated vs. measured LAI at site DIJ, GRI, KLI, LAM, and LAN. The first vertical dashed line x = 45 is defined as the end of the early crop growth period, and x = 115 is defined as the start of the late crop growth period. Between the two lines, it is defined as the middle crop growth period. Error bars are the stand error of the mean at DIJ, GRI, LAM and LAN, and are the 10% of the observations at KLI where only mean values of observations are available.

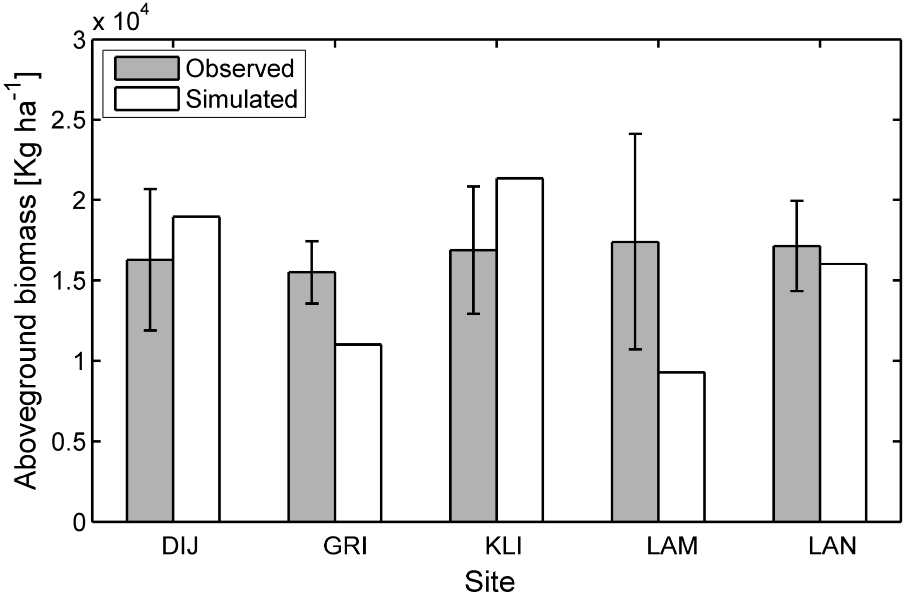

Fig. 3. Simulated (white bar) vs. measured (gray bar) above ground biomass (AGB) at harvest date. Error bars are the standard error of the mean at DIJ, GRI, LAM and LAN, and is the mean standard error of the other four sites at KLI where only mean value of observation is available.

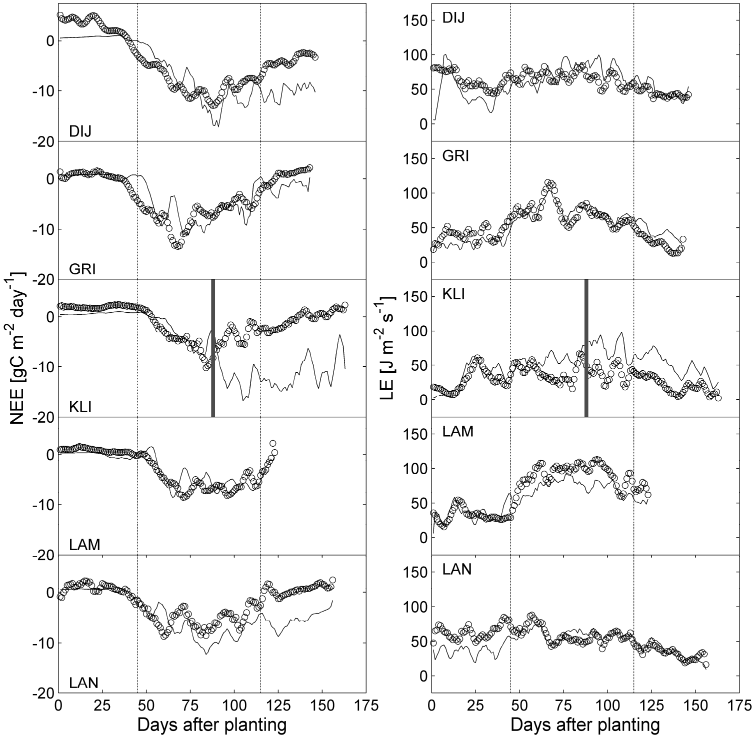

Fig. 4. Evolution of daily NEE (left) and LE (right) during the growing period at five maize sites. Circle symbols indicate eddy covariance observed values and blue line indicates values simulated by ORHICDEE-STICS. The fluxes are smoothed over consecutive 5 days. The first vertical dashed line x = 45 is defined as the end of the early crop growth period, and x = 115 is defined as the start of the late crop growth period. Between the two lines, it is defined as the middle crop growth period. The solid bold line at KLI subplot indicates the hail storm event on x = 88.

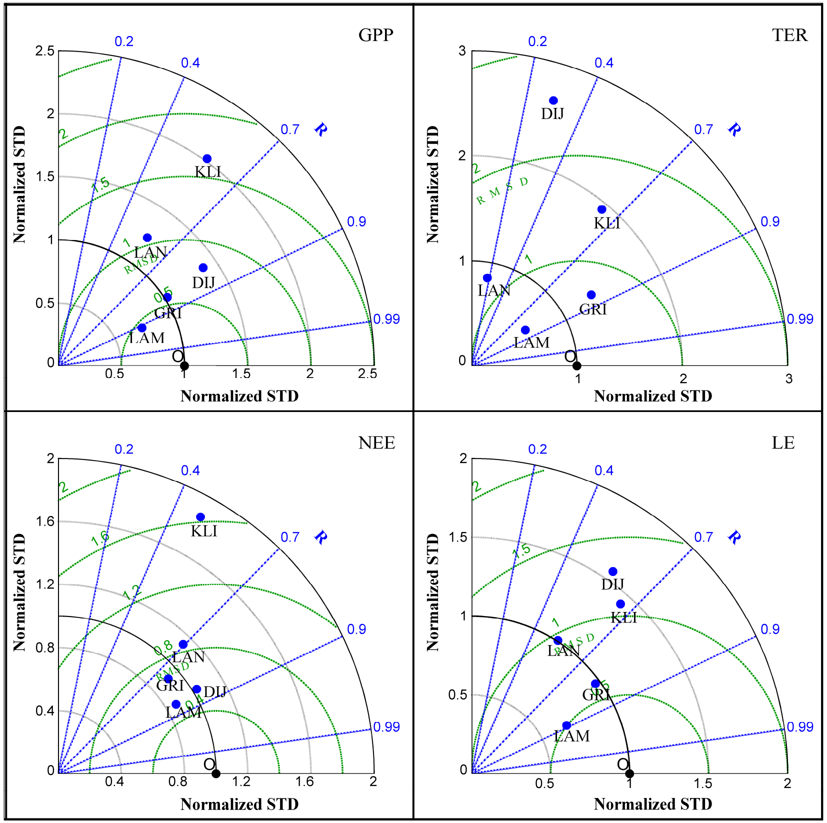

Fig. 5. Taylor diagram plot of the simulated daily GPP, TER, NEE, and LE against EC observations at five maize sites. Normalized standard deviation (STD) is defined as the simulated variables divided by the observed one. Point O is defined as the "observation". Root mean square error (RMSE) is also normalized by the observed mean value. *R* is the correlation coefficient.

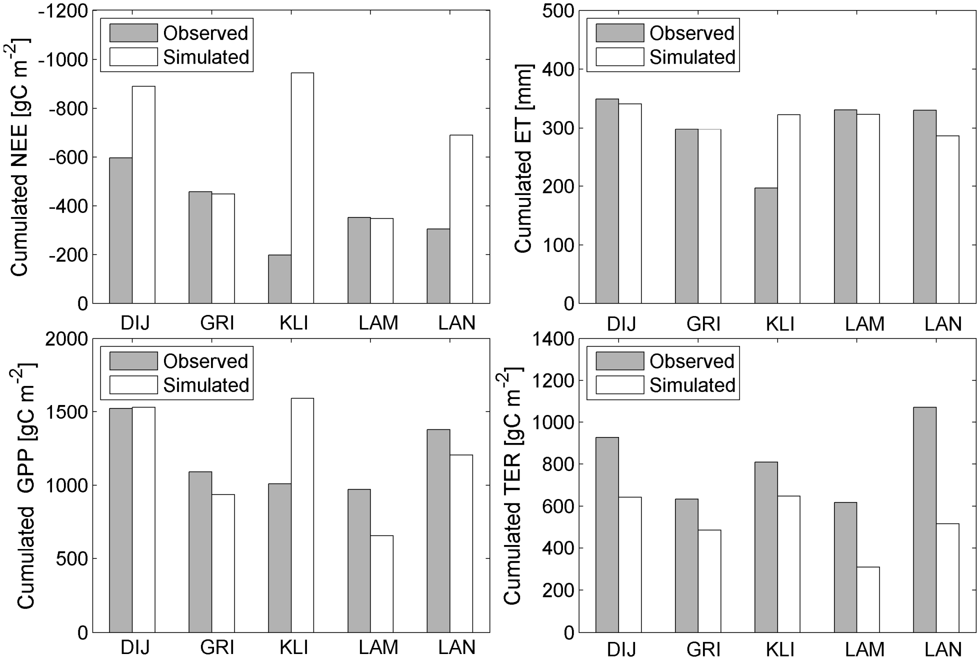

Fig. 6. Accumulated NEE, ET, GPP, and TER during the growing period. Gray bars indicate the observed values and white bars indicate the simulated ones.

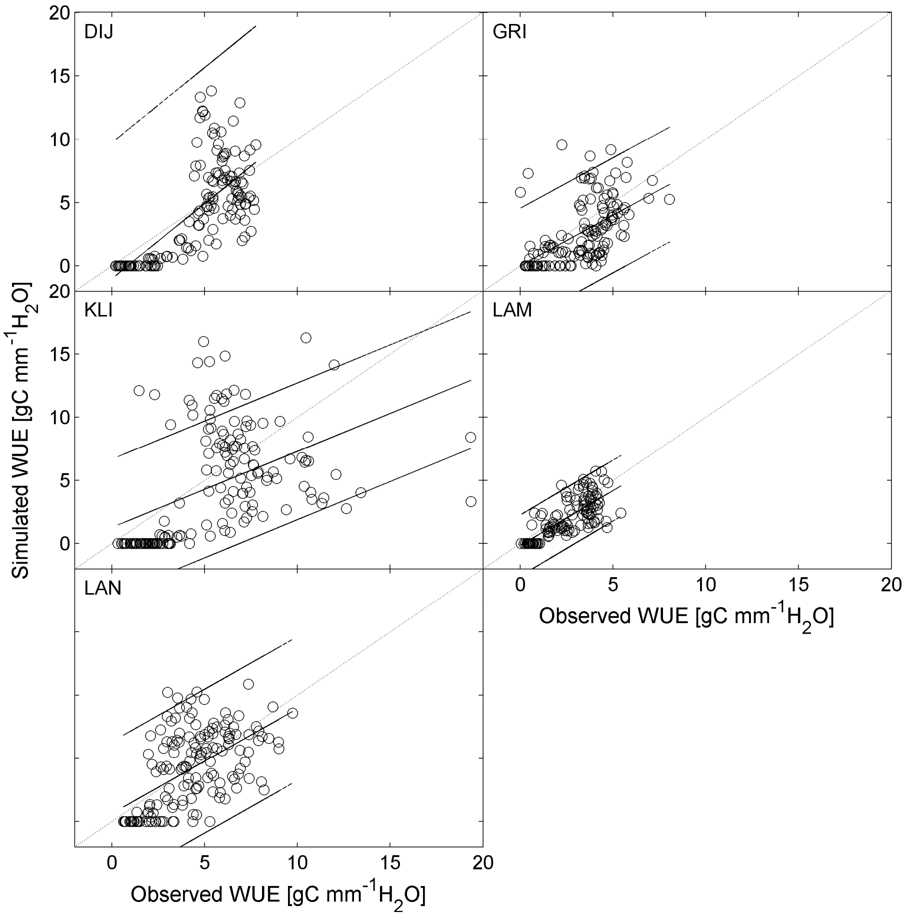

Fig. 7. Modeled vs. simulated daily average water use efficiency (WUE) at 5 maize sites. The dotted line indicates the 1:1 line. The solid line indicates the linear regression and the dashed lines represent the 3σ confidence limits.

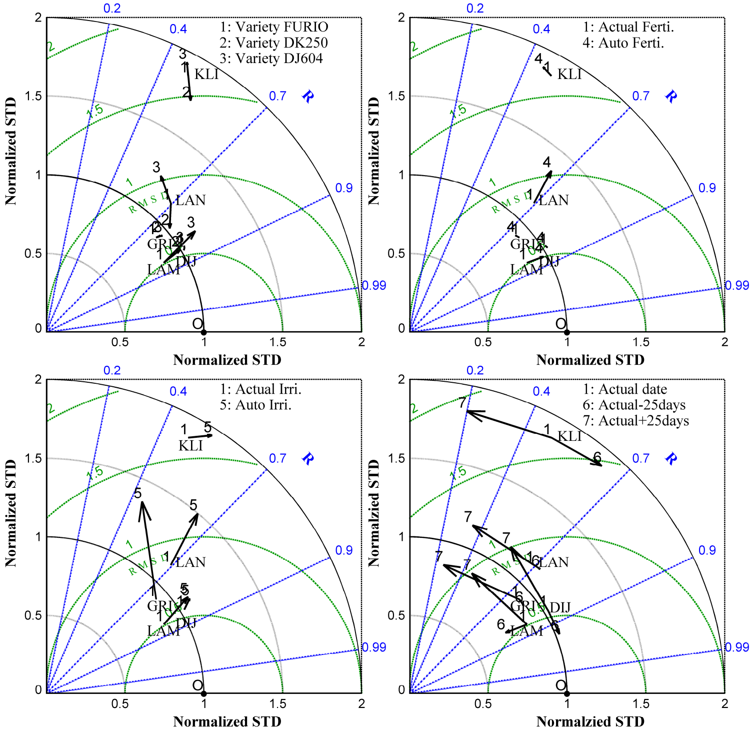

Fig. 8. Changes in normalized pattern statistics for the response of the simulated NEE to crop varieties (upper left), fertilization (upper right), irrigation (lower left), and planting date (lower right). The statistics for the management practice simulation are plotted at the tail of the arrows (number 1), and the arrows (number from 2 to 7) point to the statistics for the control simulations. At each site, the longer the arrow, the more sensitive is ORCHIDEE-STICS to a change in management parameter. Normalized standard deviation (STD) is defined as the simulated variables divided by the observed one. Root mean square error (RMSE) is also normalized by the observed mean value. *R* is the correlation coefficient.

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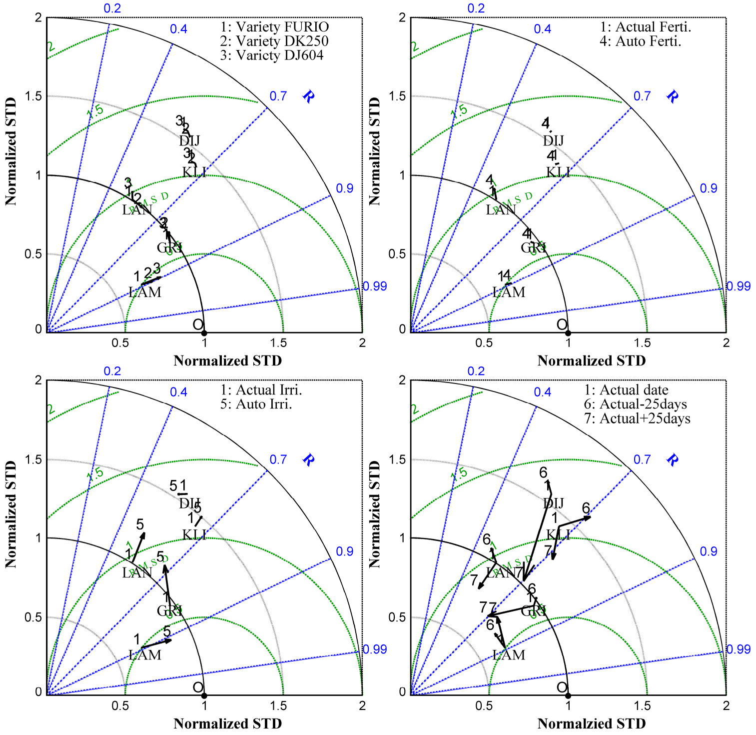

Fig. 9. Changes in normalized pattern statistics for the response of the simulated LE to crop varieties (upper left), fertilization (upper right), irrigation (lower left), and planting date (lower right). The statistics for the management practice simulation are plotted at the tail of the arrows (number 1), and the arrows (number from 2 to 7) point to the statistics for the control simulations. At each site, the longer the arrow, the more sensitive is ORCHIDEE-STICS to a change in management parameter. Normalized standard deviation (STD) is defined as the simulated variables divided by the observed one. Root mean square error (RMSE) is also normalized by the observed mean value. *R* is the correlation coefficient.

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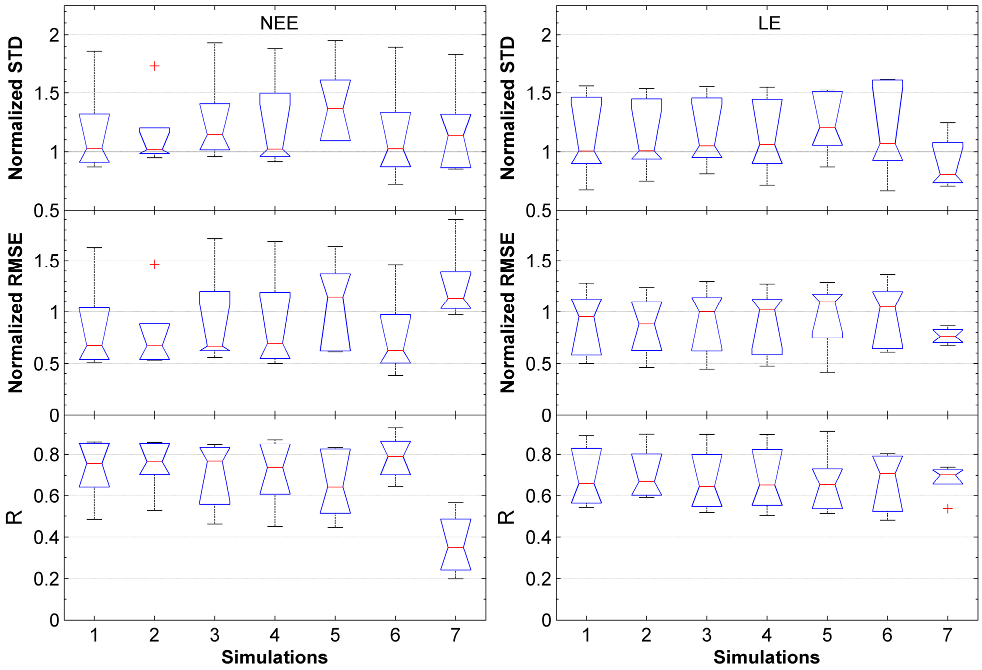

Fig. 10. The sensitivity of NEE (left) and LE (right) to crop varieties (simulations 1, 2, 3), fertilization (4), irrigation (5), and planting dates (6 for early planting and 7 for late planting). Normalized standard deviation (STD) is defined as the simulated variables divided by the observed one. Root mean square error (RMSE) is also normalized by the observed mean value. *R* is the correlation coefficient. All statistical indicators (STD, RMSE, and *R*) are computed with five maize sites. The lower and upper lines of the box indicate 25 and 75 percentiles, respectively. The thick black line in the box is the median value. The whiskers (horizontal bars beyond the box) represent 1.5 times of the interquartile range. Outliers are displayed with a red "+" sign.

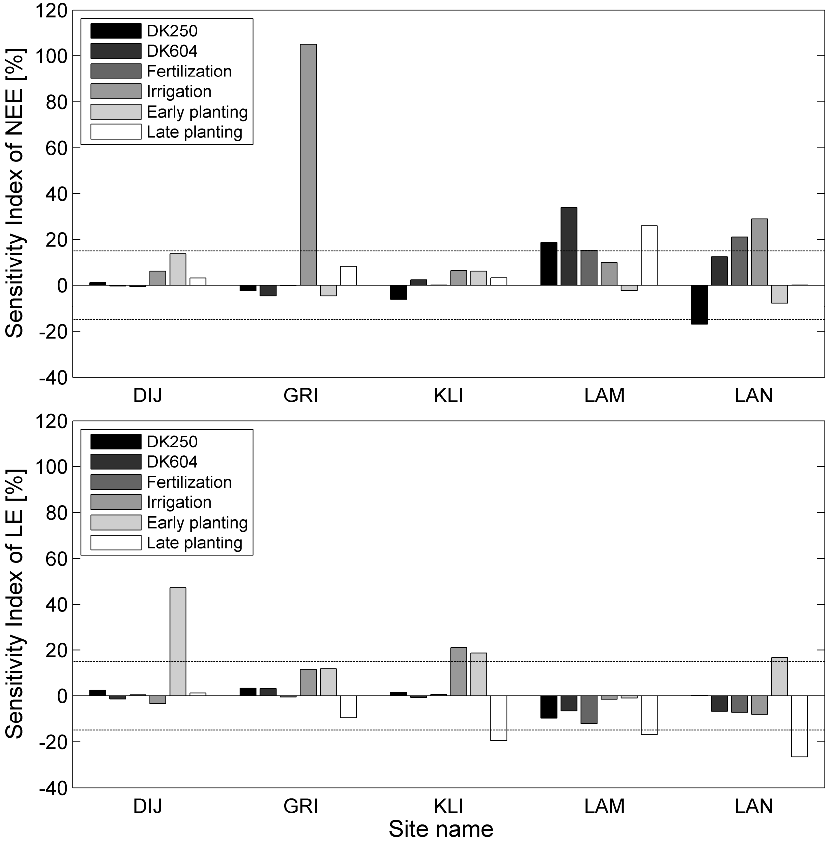

Fig. 11. Sensitivity index (SI) of cumulated NEE (upper) and LE (lower) during the growing season to different management practices. Sensitivity index is defined as the ratio of difference between "reference simulation" and "control simulation" to "control simulation". Control simulation is referred to: variety FURIO, observed fertilization, irrigation, and observed planting and harvest dates. The two horizontal dashed lines y = ±15% indicate the threshold value for significant sensitive index.