



ORCHIDEE-SRC v1.0: an extension of the land surface model ORCHIDEE for simulating short rotation coppice poplar plantations

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Abstract

Modelling biomass production and the environmental impact of short rotation coppice (SRC) plantations is necessary for planning their deployment, as they are becoming increasingly important for global energy production. This paper describes the modification of the widely used land surface model ORCHIDEE for stand scale simulations of SRC plantations.

The model uses weather data, soil texture and species-specific parameters to predict the aboveground (harvestable) biomass production, as well as carbon and energy fluxes of an SRC plantation. Modifications to the model were made to the management, growth, and allocation modules of ORCHIDEE.

The modifications presented in this paper were evaluated using data from two poplar based SRC sites. The simulations show that the model performs very well to predict aboveground (harvestable) biomass production (within measured ranges), ecosystem photosynthesis ($R^2 = 0.78$, NRMSE = 0.064, PCC = 0.89) and ecosystem respiration ($R^2 = 0.95$, NRMSE = 0.081, PCC = 0.91).

Overall, the extended model, ORCHIDEE-SRC, proved to be a tool suitable for predicting biomass production of SRC plantations.

1 Introduction

In recent years, a great deal of research has gone into the development of renewable energy as a way to sustain energy production without contributing to climate change. The Europe 2020 headline targets of the European Commission state that by 2020, greenhouse gas emissions should be 20 % lower than in 1990 and 20 % of the European energy has to be renewable (EC, 2010). The National Renewable Energy Action Plan (NREAP) predicts that in Europe 34.3 % of the electricity production and 21.3 % of the heating and cooling energy requirement will come from renewable energy production by 2020 (Zervos et al., 2011). An important share of this renewable

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energy production will come from biomass. Both annual and perennial energy crops and biomass residues from agriculture, forestry and processing industries can be used.

SRC plantations are perennial energy crops with fast growing tree species, mostly poplar (*Populus* spp.) or willow (*Salix* spp.), that are intensively managed in a coppice system (Herve and Ceulemans, 1996; Aylott et al., 2008). The rotation duration typically ranges from 2 to 5 years. At the end of the rotation the shoots are cut back to the ground in winter and the stumps resprout the next spring. The harvested wood is then dried and used for energy production. Management intensity of a SRC plantation is thus higher than in traditional forests, but less than in food crops (Hansen, 1991).

Because of the growing societal demand for energy from biomass, SRC plantations are likely to become more widespread, although the full consequences on the carbon (C), water and energy budgets are not yet fully understood. For this reason models are needed that can simulate the larger-scale effects of wide-spread SRC use, which are sufficiently general to allow application at larger scales, while being specific in the essential details.

The objective of this study is to further develop an existing land surface model called ORCHIDEE, to have the model simulate the C and water fluxes of SRC plantations over a range of site conditions. To this aim we made changes to the management, growth and allocation modules of ORCHIDEE, adjusted the parameterization and evaluated the performance of the adapted model against site-level information from two operationally managed SRC stands in Belgium.

2 Materials and methods

2.1 Model description

ORCHIDEE is a mechanistic land surface model that was designed to operate from regional to global scales. The model is composed of two components: (i) SECHIBA, which computes the energy and hydrology budget on a half-hourly basis, and

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(ii) STOMATE, which simulates the carbon cycle on a daily time scale. The equations used by ORCHIDEE are given in Ducoudre et al. (1993), Krinner et al. (2005) and in the online documentation (<http://forge.ipsl.jussieu.fr/orchidee/wiki/Documentation>). The source code can be accessed at http://forge.ipsl.jussieu.fr/orchidee/browser/tags/ORCHIDEE_1_9_5.

For these simulations, ORCHIDEE needs seven meteorological variables at a 30 min interval, i.e.: wind speed, air pressure, short-wave radiation, long-wave radiation, air temperature, precipitation and specific air humidity. Atmospheric CO₂ concentrations are required on a yearly time scale and a representative soil texture for the site is sufficient.

We evaluated the modifications to ORCHIDEE using output variables that are related to the carbon and energy balance, i.e.: Gross Primary Production (GPP), Net Ecosystem Exchange (NEE), respiration (R), sensible heat (H) and latent heat (LE).

In version r512, the C in ORCHIDEE is distributed over three main pools: (i) biomass, (ii) litter and (iii) soil carbon. These pools are divided into 8, 2 and 3 sub-pools, respectively. The biomass pool consists of leaves, roots, above- and belowground sapwood, above- and belowground heartwood, fruits (i.e. both flowers and fruits) and a carbohydrate reserve. The litter pool is composed of a structural and a metabolic litter pool. The former contains high-lignin litter, with a slow decay rate, while the latter contains low-lignin litter, which decays faster. The soil carbon consists of a fast, a slow and a passive pool, corresponding to the time it takes for the C in these pools to become biologically available again.

The soil water in r512 is simulated using two layers following the Choisnel scheme (Choisnel, 1977). The bottom layer is always present. The top layer is a dynamic layer that is absent in drier periods, and is created when it starts raining. When the top layer fills with rain, the layer expands as the soil profile becomes wetter and ultimately merges with the bottom layer.

The vegetation is classified into 12 plant functional types (Krinner et al., 2005) plus bare soil. In these plant functional types, plants with a similar physiology are grouped

together. The SRC simulations in this paper further develop the “temperate deciduous broadleaf forest” functional type.

As an extension to the standard version of ORCHIDEE, ORCHIDEE-FM was developed to include a number of adaptations for forest management (Bellassen et al., 2010). These adaptations include an age-related limitation of leaf area index (LAI) in young stands, an age-related decline in NPP, self-thinning in unmanaged stands and anthropogenic thinning in managed stands. The source code for the ORCHIDEE-FM branch can be obtained upon request (see <http://labex.ipsl.fr/orchidee/index.php/contact>).

2.2 Model modifications to SRC

2.2.1 Management modifications

A first and essential modification was the ability to simulate multiple rotations, including the coppicing of the trees (Supplement, teal sections). Under SRC, the trees are not entirely harvested. A stump of approximately 10 cm is left, from which the trees can resprout (DEFRA, 2004). To account for this, the biomass of 10 cm long stumps is calculated using Eq. (1), and remains in the aboveground woody biomass pool, instead of contributing to the exported biomass pool. Contrary to the thinning in ORCHIDEE-FM, only aboveground biomass is removed during the coppicing of a short rotation coppice.

$$f_{\text{bm_vol}} \left(\sum \frac{L \cdot \text{circ}^2}{4\pi} \right) \quad (1)$$

where L is the length of the remaining stump (0.1 m), circ is the circumference of the individual shoot, which is a variable in ORCHIDEE-FM and $f_{\text{bm_vol}}$ is an allometric function to calculate biomass from volume, as further described in Table 1.

A second modification was made for the cultivation regime at the site. In ORCHIDEE, trees start their lives as saplings. Contrary to forest tree plantations, SRC plantations

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are established using cuttings, i.e. 20 cm long hardwood sticks without any roots or leaves. The average carbon content of a cutting was estimated from the average volume and wood density to be 2.5 g of C. ORCHIDEE was modified to grow SRC from these cuttings (Supplement, turquoise sections). Half of this C is located in the above-ground sapwood pool of the cutting and the other half in the carbohydrate reserve. The number of cuttings per hectare can be defined in the configuration file when running the model.

2.2.2 Growth modifications

ORCHIDEE-FM uses five allometric relations to convert stem biomass into stem volume, stem volume into stem biomass, circumference into stem volume, stem volume into circumference and circumference into height (Table 1; Supplement, blue sections). These standard relations were parameterized using data from the Boom site, one of the two SRC sites that we used for parameterization and evaluation (see Sect. 2.3.1).

After coppicing an SRC-tree resprouts as a multi-stemmed tree. This was incorporated into the model as a second growth modification (Supplement, violet sections). The number of shoots with which the tree resprouts depends on the genotype. The variation in the number of stems resprouting after coppicing is very large, ranging from 1 to 25 (Pontailleur et al., 1999; Dillen et al., 2013). Here, we adopted an average across the many genotypes of two stems after the first coppicing and four stems after the subsequent coppicing.

A final growth adaptation was made to the fine root growth. In ORCHIDEE, the senescence of the leaves and fine roots occurs simultaneously by the same phenological trigger. For SRC simulations, we decoupled the root mortality from the leaf senescence and included a turn-over time (Supplement, yellow sections). The poplar fine roots now stay alive for six months after their formation, an average lifetime observed in the field (Coleman et al., 2000; Block et al., 2006). The onset of fine root growth remains coupled with the phenological trigger for leaf growth.

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2.2.3 Allocation modifications

A poplar tree can become sexually mature from the age of five onwards, depending on the genotype (Dickmann and Stuart, 1983; Muhle Larsen, 1963). Because the duration of most SRC rotations is under five years, SRC-grown poplars will never produce flowers or seeds. The same holds for the sapwood to heartwood conversion. To account for this in the model, no carbon is allocated to the reproduction-pool (Supplement, red sections), and no aboveground sapwood is converted into heartwood (Supplement, brown sections) when the last coppicing was less than 5 years ago.

The tree species used in SRC plantations are fast-growing tree species that reach a large leaf area as fast as they can. The standard allocation to leaves in ORCHIDEE-FM is strictly constrained by the maximum leaf area index (LAI_{max}) for that year. This LAI_{max} evolves slowly, as the stand grows and the canopy closes. The high planting density and the different phenology of poplars in SRC plantations do not fit this scheme. Data show that for SRC plantations, this limitation is only present in the first one to two years. Therefore, we adapted LAI_{max} in the model such that it is only limited in the first year, and allowed to reach the plant functional type-specific LAI_{max} from year 2 onwards (Supplement, green sections).

After coppicing, poplar trees allocate almost no carbon to the growth of coarse roots. To simulate this effect, the trees in the extended ORCHIDEE model try to maintain a prescribed, structurally logical, root-shoot ratio. When the root-shoot ratio deviates from this prescribed ratio by more than 10 %, such as after removal of the entire shoot biomass, 95 % of the C allocated to wood production is allocated to the aboveground part (Supplement, lime sections).

2.2.4 Parameterization

The default parameters in ORCHIDEE were compared to measurements from the POPFULL site (see Sect. 2.3.2). A number of parameters (Table 2) were changed based on this comparison (Supplement, pink sections). Parameters that were in the

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range of the measured data were left unchanged. A first parameter is LAI_{max} . This is the maximal LAI that the trees can reach. The next two parameters $V_{c, max}$ (maximum carboxylation rate) and J_{max} (maximum electron transport rate) are photosynthetic parameters. When these parameters are higher, photosynthesis will be higher. Finally, H_{root} is the exponential decay factor of the root profile. This parameter describes the distribution of the roots in the soil and therefore influences the water availability to the plant.

2.3 Data description

2.3.1 Boom site

The Boom site was a poplar-based SRC plantation operating from April 1996 until November 2011 in Boom, near Antwerp, Belgium (51°05' N, 4°22' E; 5 m a.s.l.). The plantation was established on a 0.56 ha former land fill, which was covered with a 2 m thick soil layer. Seventeen different poplar (*Populus* spp.) genotypes, belonging to six parentage lines, were planted in April 1996 in a double-row design with inter-row distances of 0.75 m and 1.50 m and a spacing of 0.90 m within the rows, resulting in a planting density of 10 000 cuttings ha⁻¹. The plantation was harvested in December 1996, January 2001, February 2004, February 2008 and November 2011, i.e. one establishment year and four subsequent rotations of each 4 years, 3 years, 4 years and 4 years, respectively.

At this site dendrometric measurements included aboveground biomass, tree height and circumference at 22 cm a.g.l. A more complete description of the site and the plant materials has been provided by Laureysens et al. (2003) and Casella and Ceulemans (2002). The evolution of growth, biomass production and yield has been described in detail by Dillen et al. (2011, 2013).

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2.3.2 POPFULL site

The operationally managed POPFULL site was established in April 2010 in Lochristi, near Ghent, Belgium (51°07' N, 3°51' E; 6 m a.s.l.), on 18.4 ha of former pasture and cropland. Twelve different poplar (*Populus* spp.) genotypes and 3 willow (*Salix* spp.) genotypes were planted in a double-row design with inter-row distances of 0.75 m and 1.50 m and a spacing of 1.10 m within the rows, resulting in a planting density of 8000 cuttings ha⁻¹. The plantation was harvested for the first time in February 2012.

At this site, an eddy covariance tower was erected (Zona et al., 2013a, b, 2014). The height of the tower varied between 3 m and 6 m, depending on canopy height. From this tower, CO₂ and H₂O fluxes were measured. Furthermore, leaf phenology was monitored and LAI was regularly measured. At the end of each growing season, the biomass production was estimated from stem circumference measurements and site-specific allometric relations.

A complete description of this site is given in Broeckx et al. (2012), while the eddy covariance flux measurements have been described in detail by Zona et al. (2013b, a, 2014) and the carbon budget was calculated by Verlinden et al. (2013).

2.4 Simulation setup

On the POPFULL site, meteo data for 2010 and 2011 were collected together with the eddy covariance flux data. Since the measurements did not start until June 2010, this gap was filled using data from a nearby station (Melle) from the Royal Meteorological Institute (RMI). For the Boom site, meteo data were used from a nearby field site (Brasschaat).

Before running the simulations, the model was optimised to achieve a soil C equilibrium. For this spinup the model was used without SRC modifications, with the standard “temperate deciduous broadleaf forest” plant functional type. The model was first run for 20 years, followed by 50 years with a simplified version that only contained the carbon module. This was repeated three times. Thereafter, the model was run for

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40 years, followed by 1000 years with a simplified version that only contained the soil processes and finally another 260 years of the full model. This accumulates to a total of 1510 years, of which 360 were run with the full model. In this spinup, the available meteo data was used throughout the 1510 years.

For the simulation of the POPFULL site, the soil fractions were set to the average of the measured data (86 % sand, 3 % silt, 11 % clay). For the Boom site, no texture data were available. Being a former land fill, the soil description for this site was very imprecise, mentioning only the broader texture classes, loam, sandy loam and silt loam. Therefore, the standard texture values (49% sand, 29% silt, 22% clay), which correspond to loam, were used for the Boom site. The number of cuttings was set to 8000 ha⁻¹ for the POPFULL site and 10 000 ha⁻¹ for the Boom site. The soil depth was set to 1 m for both sites.

2.5 Data processing

For the POPFULL site, measured eddy covariance fluxes (GPP, R_{eco} , NEE, H and LE) were used to evaluate the model outputs. NEE, H and LE were measured directly by the eddy covariance technique, but for GPP and R_{eco} an approximation had to be calculated using flux-partitioning. Here, GPP and R_{eco} were calculated using the online eddy-covariance gap-filling and flux-partitioning tool of the Max Planck Institute for Biogeochemistry (<http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/>), which is based on the standardized methods described in Reichstein et al. (2005).

To quantify the model fit of the modelled fluxes with the measured data, three statistical criteria for model efficiency were evaluated using the half hourly data. The coefficient of determination (R^2), the normalised root mean square error (NRMSE) and a Pearson correlation coefficient (PCC) were calculated. The root mean square error was normalised by dividing it by the range of values of the measured variable.

To visualise the model fit, the modelled fluxes were plotted against the measured weekly averages.

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To compare the total fluxes, the half hourly data were cumulated. Since there were no flux measurements before June 2010, this gap was filled with the modelled data.

3 Results and discussion

The relative impact of the model modifications on the accuracy of the model simulations by the extended model, ORCHIDEE-SRC, relative to ORCHIDEE-FM is presented in Fig. 1. Biomass production and all fluxes were simulated better or equally well by the extended model. Figure 2 also shows the improvement in the simulation of biomass production compared to ORCHIDEE-FM. Detailed analysis of the model simulations of biomass production, carbon fluxes and energy fluxes are given in the sections below.

3.1 Biomass evaluation

For the Boom site, the yearly aboveground biomass measurements were compared to the model output (Fig. 2a). From the third year of the first rotation onwards, the model predictions were well within the range of measured values and approximate the average aboveground woody biomass production. Measurements were available for 17 genotypes, hence the wide range in observations. The low measured values in the first two years might be explained by strong competition from weeds, which was observed in the starting years of this plantation (R. Ceulemans, personal communication, 2013). The low values for the year 1998 – a cold wet year – are explained by a severe rust infection at the site (Al Afas et al., 2008).

The modelled aboveground biomass for the POPFULL site was also well within the measured ranges (Fig. 2b), although the prediction for the first year was in the lower limits of the range.

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3.2 CO₂ flux evaluation

The measured C and energy fluxes at the POPFULL site were compared to the model outputs. Figure 3 depicts both the simulated and observed cumulative GPP, NEE, H , LE and R_{eco} .

During the first year, the calculated and observed GPP values matched well ($R^2 = 0.78$, NRMSE = 0.064, PCC = 0.89; Fig. 3). In winter, measured values established a slight increasing trend, while GPP remained constant in the model outputs. This could either be explained by photosynthesis of weeds, which are not represented in the model, or by errors in the flux partitioning. This difference can also be seen in Fig. 4; the vertical column of measured values that corresponds to the $0\text{ g C m}^{-2}\text{ week}^{-1}$ in the simulated GPP were caused by this winter CO₂ uptake. During the second year, the modelled GPP started rising about one month later than the measured values, but thereafter caught up with the measurements (Fig. 3). Again, this difference might have been caused by the presence of weeds in the field, which were not accounted for in the model. Another reason for these differences could be the use of different genotypes at the field site, while the model only simulates an average genotype. In 2011, the spring bud flushing date of the different genotypes ranged from day 72 until day 107, which is about a one month difference. The modelled bud flush started on day 97, which is well within this observed range, but logically results in a lag of 25 days between observed and simulated date of onset of GPP. After two years, the cumulated GPP values were 22.6 Mg C ha^{-1} and 21.4 Mg C ha^{-1} for the model and the measurements, respectively. This difference of 1.2 Mg C ha^{-1} , represents an overestimation by the model of only 5%, well within the uncertainty of eddy covariance-based GPP estimates (Desai et al., 2008; Richardson et al., 2006). Figure 4 also clearly shows that the modelled values compare well with the measured values, apart from a slight overestimation at the high GPP fluxes.

The modelled R_{eco} fitted the measurements very well ($R^2 = 0.95$, NRMSE = 0.081, PCC = 0.91). The only point of divergence was the dry spell in the summer of the

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second year. Here, R_{eco} was underestimated, probably because the model is too sensitive to drought. Figure 4 shows this slight underestimation at high R_{eco} values. The accumulated R_{eco} for the first rotation based on observations was $24.0 \text{ Mg C ha}^{-1}$, while the model predicted $23.1 \text{ Mg C ha}^{-1}$; an underestimation of only 4%.

When comparing NEE, the fit is less good than for GPP and R_{eco} ($R^2 = 0.51$, NRMSE = 0.069, PCC = 0.84). In the model results, the plantation switched from emitting C to taking up C in July of the first year. In the measured data, this switch occurred only during August, possibly because of the increased C loss due to the land use change after the plantation establishment (Zona et al., 2013a). During the winter and spring of the second growing season, both the simulated and the measured fluxes indicated a net loss of CO_2 , but the simulation suggested a stronger source. This difference could probably be explained by the presence of weeds on the site, which were not present in the model simulation. The photosynthesis of these weeds partly counteracted the C losses from soil respiration. From August until October, both the model and the measurements indicated a C uptake. The model, however, presented a stronger C sink than the measurements. From October onwards, both modelled and measured data showed a C source. At the end of the second year, the end of the first rotation, the measurements showed a cumulated net C loss of 5.4 Mg ha^{-1} , while the model only predicted a C loss of 2.5 Mg ha^{-1} . The model underestimated the C loss to the atmosphere by 49%.

3.3 Water and energy flux evaluation

For H , the cumulative plot (Fig. 3) shows diverging lines and an overestimation of 120% of the cumulative energy loss from H at the end of the rotation ($R^2 = 0.28$, NRMSE = 0.061, PCC = 0.74). Looking at Fig. 4, it is clear that this is caused by a constant overestimation of H . Because H has no impact on the C or water cycle in the model algorithms, this problem was not considered an issue in this study.

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During the first growing season, LE increased slower in the model than can be observed in the measured data ($R^2 = 0.67$, NRMSE = 0.056, PCC = 0.78; Fig. 3). This might be explained by the LAI. The modelled LAI ($LAI_{\max} 0.75$) for the first year was on the lower end of the measured LAI ranges ($LAI_{\max} 0.6\text{--}1.8$). This lower leaf area consequently resulted in a lower leaf surface to evaporate water from. From November of the first year onward, the cumulative LE curves of the simulations and the measurements keep running in parallel, except for a small period during the second year. This was caused by a dry spell during August. The model slightly underestimated the effect of the drought, allowing the trees to transpire more water. This can be observed in Fig. 4, as the four overestimated dots between 60 and 80 W m^{-2} . At the end of the rotation, this resulted in a cumulative LE of 880 kW m^{-2} for the measurements and 830 kW m^{-2} for the model, which is an underestimation of 6% by the model.

4 Conclusion

The adaptations to the model ORCHIDEE presented in this paper were evaluated using data from two field sites. The simulations show that the model performs well to predict aboveground (harvestable) biomass. Also gross primary production ($R^2 = 0.78$, NRMSE = 0.064, PCC = 0.89) and ecosystem respiration ($R^2 = 0.95$, NRMSE = 0.081, PCC = 0.91) were simulated very well. The modelled soil moisture and latent heat flux differed for certain periods during the year, but annual latent heat flux was reasonably well simulated. For a still unknown reason, the sensible heat seems to be continuously overestimated. Overall the SRC-version of the ORCHIDEE model is very well suited to simulate biomass production in SRC plantations.

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ORCHIDEE-SRC v1.0

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[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)**Table 1.** Allometric relations used for the SRC simulation in the ORCHIDEE-FM model and their parameter values. SRC = short rotation coppice culture.

Formula	Parameter	Value	Unit
$f_{\text{vol_bm}} \rightarrow \text{volume} = \frac{\text{biomass}}{\text{density}}$	density	1.25×10^5	g C m^{-3}
$f_{\text{bm_vol}} \rightarrow \text{biomass} = \text{volume} \cdot \text{density}$			
$f_{\text{vol_circ}} \rightarrow \text{volume} = \sum \frac{a \left(\frac{\text{circumference}}{\pi} \right)^b}{\text{density}}$	density	1.25×10^5	g C m^{-3}
$f_{\text{circ_vol}} \rightarrow \text{circumference} = \pi \left(\frac{\text{volume} \cdot \text{density}}{a} \right)^{1/b}$	a	0.033	
	b	2.6	
$f_{\text{height_circ}} \rightarrow \text{height} = a \cdot \text{circumference}^b$	a	17.2684	
	b	0.6791	

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Table 2. Parameter values that were changed between the standard version of ORCHIDEE-FM and the adapted version for SRC simulation. LAI_{\max} = maximal leaf area index, $V_{c, \max}$ = maximum rate of carboxylation, J_{\max} = maximum electron transport rate, H_{root} = exponential decay factor of the root profile.

Parameter	Unit	ORCHIDEE PFT 6	ORCHIDEE-SRC
LAI_{\max}	$\text{m}^2 \text{m}^{-2}$	4.5	2.5
$V_{c, \max}$	$\mu\text{mol m}^{-2} \text{s}^{-1}$	55	130
J_{\max}	$\mu\text{mol m}^{-2} \text{s}^{-1}$	70	180
H_{root}		0.8	1.5

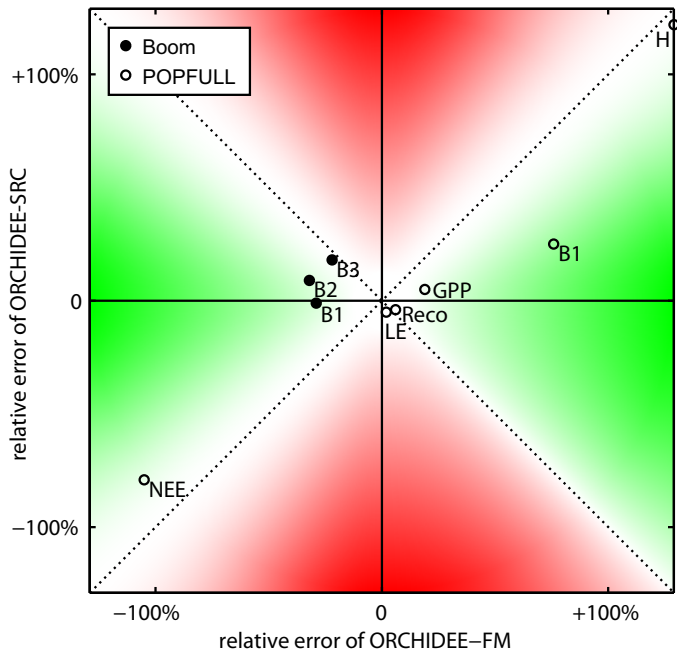


Figure 1. Comparison between the performance of the ORCHIDEE-SRC and ORCHIDEE-FM. The relative error was calculated as the relative difference between the field measurements and the model simulations. The green background indicates an improvement by the extended model relative to ORCHIDEE-FM, the red background indicates a deterioration of the model results from the extended model. A darker colour indicates a more pronounced difference. The Boom site simulations are shown as filled circles and the POPFULL site simulations are shown as open circles. The letters next to the symbol are: GPP = gross primary productivity cumulated over the two measurement years; Reco = ecosystem respiration cumulated over the two measurement years; NEE = net ecosystem exchange cumulated over the two measurement years; LE = latent heat cumulated over the two measurement years; H = sensible heat cumulated over the two measurement years; B_x = aboveground woody biomass production of rotation x .

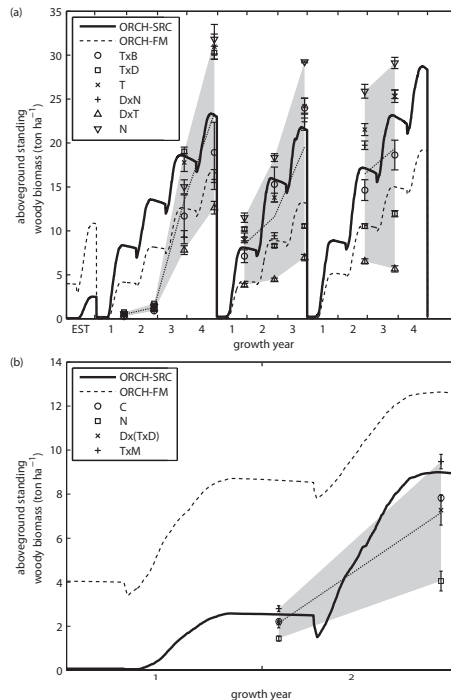


Figure 2. The simulated standing aboveground woody biomass **(a)** for the Boom site and **(b)** for the POPFULL site. The solid black line is the biomass simulated by the extended model, ORCHIDEE-SRC. The dashed line is the biomass simulated by the standard version of ORCHIDEE-FM, with only coppicing implemented. The symbols are the different parentages of the poplars at that site and the gray area is the range of measured biomasses. The parentages are *Populus trichocarpa* × *P. balsamifera* ($T \times B$), *P. trichocarpa* × *P. deltoides* ($T \times D$), *P. trichocarpa* (T), *P. deltoides* × *P. nigra* ($D \times N$), *P. deltoides* × *P. trichocarpa* ($D \times T$), *P. nigra* (N), *P. canadensis* (C), *P. deltoides* × (*P. trichocarpa* × *P. deltoides*) ($D \times (T \times D)$), *P. trichocarpa* × *P. maximowiczii* ($T \times M$).

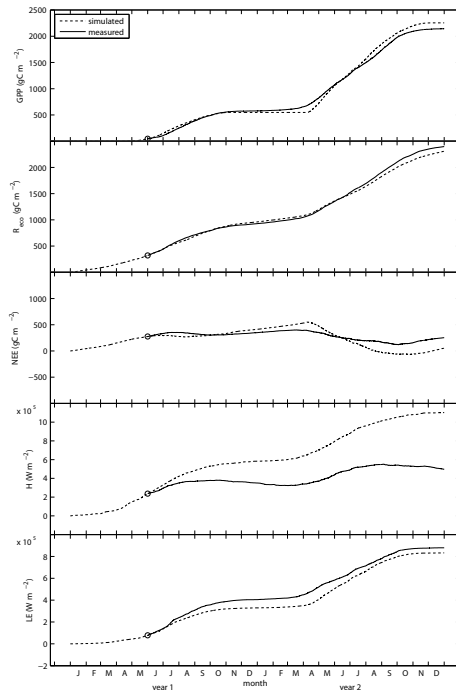


Figure 3. Cumulative fluxes of gross primary production (GPP), ecosystem respiration (R_{eco}), net ecosystem exchange (NEE), sensible heat (H) and latent heat (LE) for the POPFULL site. The solid lines are the measured values from the eddy-covariance measurements or recalculated from these measurements using the flux-partitioning tool of the Max Planck Institute for Biogeochemistry (<http://www.bgc-jena.mpg.de/~MDI/work/eddyproc/>). The dashed line are the model outputs. Since there were no flux measurements before June 2010, both simulated and measured values coincide before that date.

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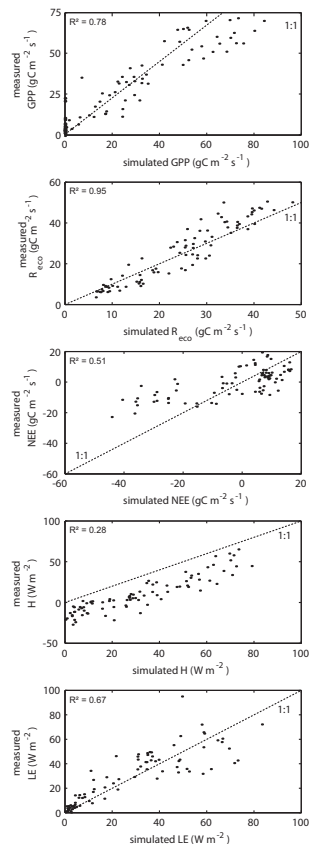
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Figure 4. A 1-to-1 comparison of weekly averages of gross primary production (GPP), ecosystem respiration (R_{eco}), net ecosystem exchange (NEE), sensible heat (H) and latent heat (LE) for the POPFULL site, between the model outputs and the measured values. The dotted line is the 1 : 1 line.