Responses to comments of referee #1

Dear Prof. Jansson,

Thank you very much for your in-depth suggestions and constructive criticism. We appreciate the time you put into reviewing our manuscript. Below you can find a point by point reply to your comments, addressing your questions and indicating our revisions to the manuscript.

General Comments

Comment:

> *The paper is demonstrating how a modified version of the Orchidee-FM was developed to describe a common short rotation forest. The Orchidee model is developed for global land surface applications and the current paper deals with an updating to not only a new forest management scheme but also to a local scale of two sites in the same climate region of the world. In the objective it is clearly stated that the purpose was to modify the model to now cover a range of site conditions for SRC systems. Two modules (Allocation are changed that are related not only to parameters but also to the structure of the model. Both of those are typically very empirical in forest modelling and not always easy to describe also for more conventional forest management systems. The paper does not make any review of process oriented modelling of SRC system on a plot scale. Many such have been made for both water, carbon and nitrogen studies.*

Response:

> We are aware that process-based models exist that probably simulate productivity of SRC plantations very well. However, these are often heavily parameterized with site-specific information. Our aim was to develop a generalized SRC model that is capable of simulating SRC under a range of site conditions, not requiring site-specific parameterization. For this reason, we did not review the existing literature for these models. However, if the referee believes that this is a condition sine qua non, we would be willing to include one or a few paragraphs describing the process-based, plot-scale models.

Changes to the manuscript:

> /

Comment:

> *Instead it makes use of mainly eddy flux data from 2 recently established sites to support a modifications. The paper is of high interest for users and developers of the Orchidee model but the general interesting issues for how to model SRC systems is lacking.*

Response:

> In our revised version, we included data from several additional sites for the validation of the biomass production. Because more continuous SRC flux measurements were not available, we could only validate our modeled fluxes for one site. For the biomass production, we initially only provided predictions for 2 sites and we admit this was not enough. Therefore,

we added an extra section, where we compare model predictions and site measurements[1] for a number of additional sites in a North-South gradient across Europe (FIG A).

Changes to the manuscript:

Lines 245-262, 340-357, 584-585, 612-615

Fig. 3

Table 3

Specific Comments

Comment:

The evaluation criteria for the acceptance of the new model is based on simple conventional statistics. Those statistics shows to my understanding only to what extent the seasonal course of the major fluxes can be described by the model. The improvement with respect to the conventional Orchidee PFT 6 is described without considering the methods for calibration. The authors need to clarify why the evaluation criteria was selected and to what extent the subjective evaluation of those conventional statics is a very well performing model and this proved to be useful tool to predict biomass productions for SRC plantations in general.

Response:

Our original aim was mainly to show how well a general model could reproduce productivity of SRC plantations and not to really to compare is with ORCHIDEE-FM. We believe that conventional statistics suffice to describe the performance of our model. The coefficient of determination (R^2) explains the variance in model performance by comparing it to the data variation. The normalized root mean square error (NRMSE) gives a measure for the accumulated model error. The Pearson correlation coefficient (PCC) shows how well the data is correlated. While R^2 and PCC give a measure for how well the trends in the data are simulated, NRMSE gives a measure for the total cumulated model error. We updated our description of the used statistics in the materials and methods section of the manuscript to include this.

Changes to the manuscript:

Lines 308-311

Comment:

The authors are recommended to evaluate the model on NEE rather than ecosystem respiration and photosynthesis. Otherwise please justify the meaning of the separate components. . .

Response:

Figure 3 (now figure 4) shows the cumulative, absolute comparison of NEE measured and modeled, and figure 1 shows their relative agreement. So we do evaluate NEE and the result is not very good, which is not surprising, because it is the small difference between two large (and uncertain) fluxes: GPP and R_{eco}. Since NEE is the sum of two big fluxes, one positive and one negative, small deviations in the carbon modeling are exaggerated in the NEE output. For example, a GPP of 50 gC m^{-2} y^{-1} and a R_{eco} of 40 gC m^{-2} y^{-1} results in a NEE of 10 gC m^{-2} y^{-1},

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[1] S. Njakou Djomo, A. Ac, T. Zenone, T. De Groote, S. Bergante, G. Facciotto, H. Sixto, P. Ciria Ciria, J. Weger, R. Ceulemans, Energy performances of intensive and extensive short rotation cropping systems for woody biomass production in the EU, Renewable and Sustainable Energy Reviews, Volume 41, January 2015, Pages 845-854, ISSN 1364-0321, http://dx.doi.org/10.1016/j.rser.2014.08.058.

although the total amount of exchanged C is 90 gC m^{-2} y^{-1}. Moreover, we chose to evaluate the model using photosynthesis (GPP) and ecosystem respiration (R_{eco}) because they are the real (and large) physical fluxes that occur in the field, and are simulated by the model. The sum of these fluxes results in NEE. Therefore, we chose to put more emphasis on evaluating those, although we also show and discuss NEE. Moreover, for simulation of bio-energy production, GPP and R_{eco} are relevant and NEE is not. It is, however, relevant for C sequestration. We updated the manuscript section on CO_2 flux evaluation to clarify the meaning of these three fluxes.

Changes to the manuscript:

Lines 386-388, 404-406

Comment:

The more detailed evaluation of the model showed some major problems that are of higher scientific interest. 1)The Seasonal courses as presented in Fig 3. Showed interesting deviations between simulated and measured fluxes. Most obvious was with respect to Sensible heat flux. NEE, LE and H all shows substantial differences in the seasonal patterns. Since only those represent the original measured variables it would be of high interest to know why they were not used to evaluate the quality of the model performance.

The discrepancy with respect to sensible heat flux was disregarded by the authors since they argued that it did not have any coupling to C or Water cycle in the model. This statements needs clarifications. The sensible heat flux is normally fully linked in an energy balance equations. And if considered in the model it should have some meaning for other components. I suppose the sensible heat flux should be consistent with the surface temperature of the site. This section is recommended to be excluded from the paper if it can’t be justified from a reasonable interpretation. Maybe the particular boundaries to the specific sites are representing a scale for which we can’t close the energy balance or something is wrong in measurements or in the model.

Response:

We prefer to leave the sensible heat flux in our manuscript for transparency. We agree that the discrepancy in sensible heat flux deserves more explanation. Therefore we extended the section on the sensible heat flux. The error is probably caused by a stable stratification that often develops in dense plantations at night. Because of this stratification the measured sensible heat flux is lower than the simulated flux. We added an insert to figure 3 (now figure 4) in the manuscript that shows the average diurnal pattern of the sensible heat flux, which clearly shows this (FIG B). To get a better fit, we tuned the leaf albedo and added this to the list of changed parameters (table 2). This modification only caused very minor changes to the other simulations, but we updated the graphs and values. The stratification cannot be represented correctly by the calculation of surface drag, in the way it is implemented in ORCHIDEE. This problem did already exist in the model, as described by Krinner (2005)[2].

We also added a graph showing the measured and modeled soil temperature during 2011 for the POPFULL site. This is the only data we had on soil temperature. This data shows that the

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[2] Krinner, G., N. Viovy, N. de Noblet-Ducoudré, J. Ogée, J. Polcher, P. Friedlingstein, P. Ciais, S. Sitch, and I. C. Prentice (2005), A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, Global Biogeochem. Cycles, 19, GB1015, doi:10.1029/2003GB002199.

soil temperature was simulated very well by our model (R^2 = 0.955, NRMSE = 0.098, PCC = 0.907; FIG C.A).

We reduced figure 4 (now figure 5) of our manuscript to only show the data for the latent heat flux and highlighted the data points corresponding to the dry spell, which shows the origin of the deviation in latent heat flux simulation (FIG D).

Changes to the manuscript:

§1:
- Lines 413-418
- Fig. 4
- Table 2

§2:
- Lines 238, 435-448, 633-639
- Fig. 6

§3:
- Fig. 5

Comment:

2) The evaluation is fully lacking information about state variables in the soil. One such is the soil temperature and soil moisture and another is the root depth and allocation of carbon to the fine root system. This may be one of the most interesting components to be compared with an conventional forest site. I expect some comments to those soil conditions and especially with respect to the modified allocation procedure that was suggested for the orchidee-SRC model.

Response:

We added a section about soil variables. For this section we compared model simulations and site measurements of soil moisture and soil temperature of 2011 for the POPFULL site. This is the only field data we have on soil temperature and soil moisture. We described the soil temperature in the previous response paragraph.

For soil moisture, ORCHIDEE has only two soil compartments, of which one is only present after rainfall. Therefore, we plotted (FIG C.B) the modeled soil water content of the bottom compartment (dotted line) and the soil water content of both compartments (solid line) against the range of soil water content measurements up to 50 cm depth (gray area). We then compared the total simulated soil water content to the average measured soil water content, which had a reasonable fit (R^2 = 0.976, NRMSE = 0.152, PCC = 0.828). Due to the simplicity of the soil moisture simulation, the model cannot simulate the level of detail that is shown by the measurements. The model does show very clearly the decline of soil water content during the dry spell, and the replenishment of the top layer with the precipitation after the dry spell.

In ORCHIDEE, there is no rooting depth. Roots are assumed to span the full soil depth. We did not have any data on fine root allocation.

Changes to the manuscript:

Lines 238, 435-448, 633-639
Fig. 6

Concluding remarks

Comment:

The paper demonstrates a first approach to develop a global model to a specific forest management system. However to make the model of general interest outside the internal modeling community for the Orchidee groups it needs substantial modifications. As an internal working document the paper may be useful.

Response:

The results of our model validation are not that relevant to the modeling community, but our model modifications are. We describe process and parameter modifications to render a land surface model suitable for SRC system simulation. Our description in section 2.2 and the values in tables 1 and 2 of the manuscript are of interest to other modeling groups.
We hope that our modifications to the manuscript are satisfactory to you to consider its publication in GMD.

Changes to the manuscript:

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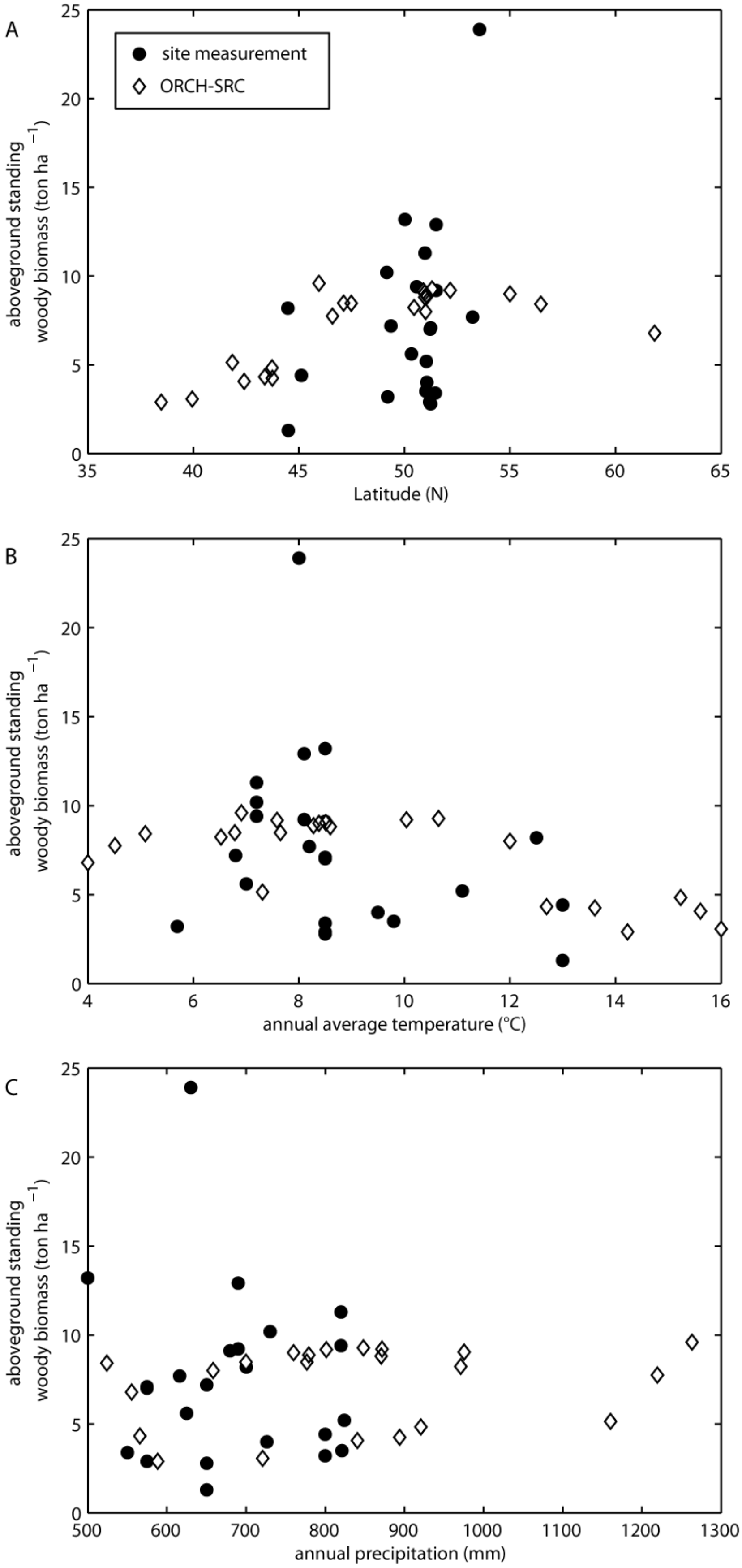

Fig. A: Comparison of aboveground standing woody biomass for ORCHIDEE-SRC simulations (open diamonds) across Europe with site measurements (black circles) across Europe. The biomass is plotted against (A) latitude, (B) annual average temperature and (C) annual precipitation.

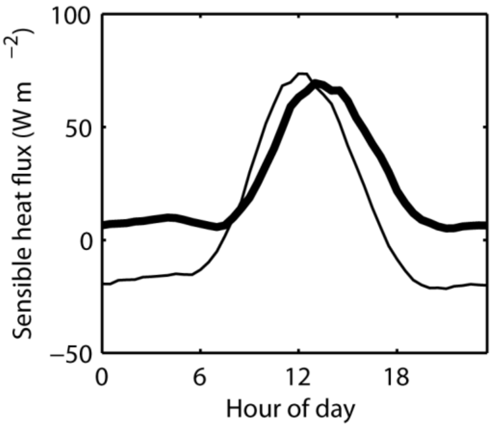

Fig. B: Insert for Figure 3 (now figure 4), showing the average diurnal cycle of the sensible heat flux. Thin line: measurements, fat line: simulations.

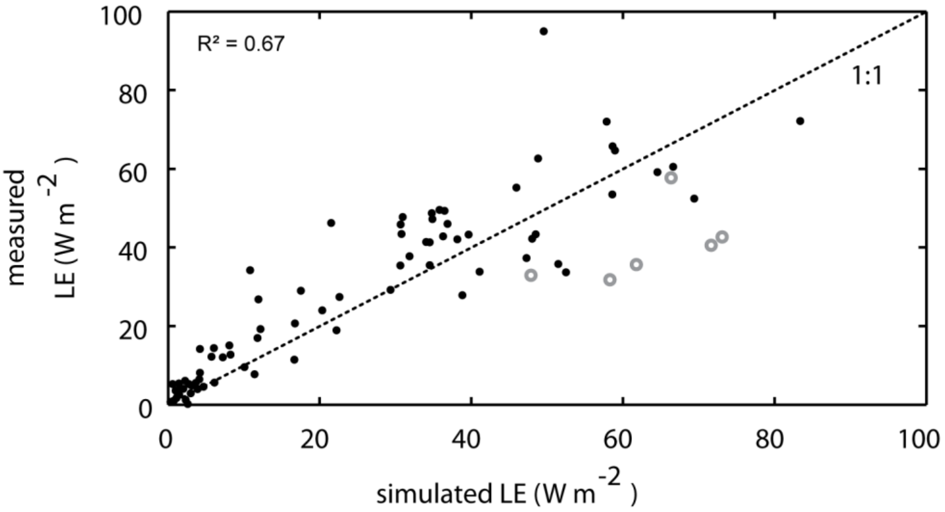

Fig. D: A 1-to-1 comparison of weekly averages of latent heat (LE)for the POPFULL site, between the model outputs and the measured values. The dotted line is the 1 : 1 line. Weeks 18-23 which represent the dry spell are highlighted as grey circles.

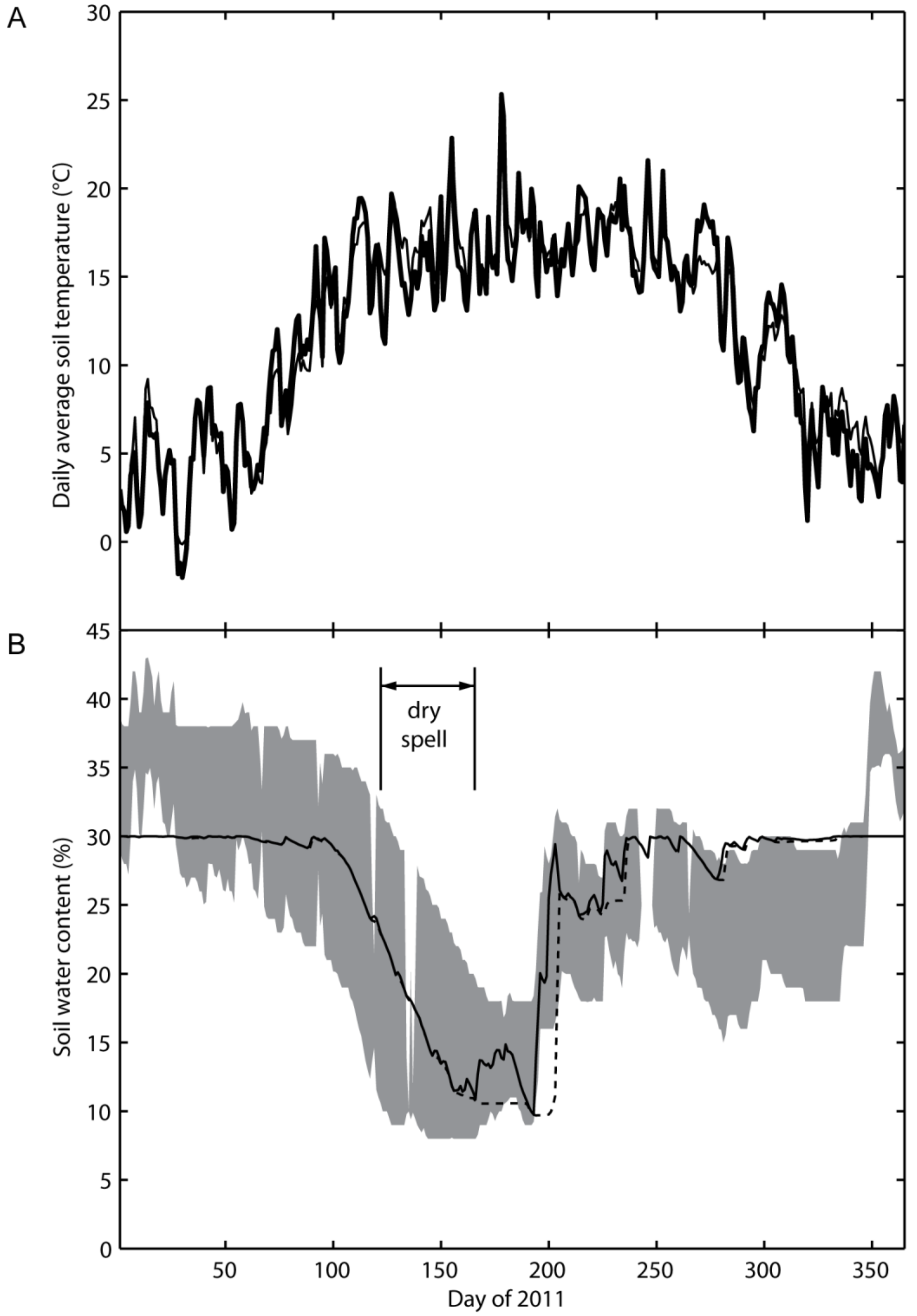

Fig. C: A comparison of modeled and measured soil state variables for 2011 at the POPFULL site. (A) shows the daily average soil temperature simulated (fat) and measured (thin). (B) shows the soil water content. The gray area represents the measured range of soil water content values for the top 50 cm of the soil. The dotted line is the soil water content of the lower water compartment of the model and the solid line is the total soil water content of the upper and lower water compartment.

Responses to comments of referee #2

Dear referee,

Thank you very much for your in-depth suggestions and constructive criticism. We appreciate the time you put into reviewing our manuscript. Below you can find a point by point reply to your comments, addressing your questions and indicating our revisions to the manuscript.

Comments

Comment:

> *1. I suggest to review the literature again for more data on poplar plantations to use for model validation. For example Searle et al. (2014, http://dx.doi.org/10.1016/j.biombioe.2014.01.001) provide a good overview and Nair et al. (2012) introduced the Biofuel Ecophysiological Trait and Yield Database (BETY-db) maintained by the University of Illinois. You should find enough information to validate ORCHIDEE-SRC under a range of climatic conditions.*

Response:

> We agree that the validation we provided was a not extensive enough to validate our model under a range of site conditions. Because more continuous SRC flux measurements were not available, we could only validate our modeled fluxes for one flux site. Biomass yield values are easier to acquire. Therefore, we added an extra section, where we compare model predictions and site measurements for a number of additional sites in a North-South gradient across Europe. We consulted the data sources you provided and the database looked promising, however, it did not contain many useful data on poplar. We therefore used another recent source of SRC yield data (Njakou Djomo (2015)[1]; FIG A).

Changes to the manuscript:

> Lines 245-262, 340-357, 584-585, 612-615
> Fig. 3
> Table 3

Comment:

> *2. Searle et al. (2014) also show that yields observed on small, intensively managed test sites may not be achieved at commercial scales. You could test the performance of simulated SRC crops using parameters of their corresponding plant functional types in natural vegetation (temperate broadleaf summergreen tree?).*

Response:

> The POPFULL site, which we used to calibrate part of our model and to validate the fluxes is run as a commercial scale plantation. Because the model performed well at this site, we think our model is suited to simulate commercial scale plantations. As requested, figure 2 of our manuscript shows a dotted line for the simulations using the standard parameterization, with

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[1] S. Njakou Djomo, A. Ac, T. Zenone, T. De Groote, S. Bergante, G. Facciotto, H. Sixto, P. Ciria Ciria, J. Weger, R. Ceulemans, Energy performances of intensive and extensive short rotation cropping systems for woody biomass production in the EU, Renewable and Sustainable Energy Reviews, Volume 41, January 2015, Pages 845-854, ISSN 1364-0321, http://dx.doi.org/10.1016/j.rser.2014.08.058.

only coppicing implemented. We also added this line to figure 3 (now figure 4) of our manuscript (FIG B).

Changes to the manuscript:

Fig. 4

Comment:

3. Please explain in more detail the longer-term purpose of developing ORCHIDEEFM. As ORCHIDEE is part of a coupled earth system model do you plan to use the model in coupled mode to study climatic feedbacks from changes in albeo, latent and sensible heat fluxes, CO2 and other greenhouse gas emissions? If this is a goal, then the problems with modelling surface heat fluxes need to be fixed first.

Response:

Our model will not be run in coupled mode. Our aim was to use this model to test a number of management scenarios across Europe to study the variation in the management effects on biomass production and CO2 uptake and find an optimal management. We expanded the section about the aim of our model development in the manuscript.

We agree that the discrepancy in sensible heat flux deserves more explanation. Therefore we extended the section on the sensible heat flux. The error is probably caused by a stable stratification that often develops in the dens plantation at night. Because of this stratification the measured sensible heat loss is lower than the simulated loss. We added an insert to figure 3 (now figure 4) in the manuscript that shows the average diurnal pattern of the sensible heat flux, which clearly shows this (FIG B insert). To get a better fit, we tuned the leaf albedo and added this to the list of changed parameters (table 2). This modification only caused very minor changes to the other simulations, but we updated the graphs and values. The stratification cannot be represented correctly by the calculation of surface drag, in the way it is implemented in ORCHIDEE. This problem did already exist in the model, as described by Krinner (2005)[2].

Changes to the manuscript:

§1:

Lines 68-70

§2:

Lines 206-208, 413-418, 596-600

Fig. 4

Table 2

Comment:

4. Changes in soil carbon under different land use options are an important determinant of the overall carbon effects of land use change. How do soil carbon pools change under SRC compared to natural vegetation and croplands in ORCHIDEE-SRC?

Response:

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[2] Krinner, G., N. Viovy, N. de Noblet-Ducoudré, J. Ogée, J. Polcher, P. Friedlingstein, P. Ciais, S. Sitch, and I. C. Prentice (2005), A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, Global Biogeochem. Cycles, 19, GB1015, doi:10.1029/2003GB002199.

These data were not available for the Boom site. On the POPFULL site, the measured soil C loss was 703 g m^{-2} for the top 15 cm [3], while the model predicted a soil C loss of 744 g m^{-2} over the first rotation. We added this to the CO_2 flux validation section of our manuscript.

Changes to the manuscript:

Lines 406-408

Comment:

5. Make sure to differentiate between calibration and validation. I think you used the eddy flux data from the POPFULL site to calibrate the model. If this is the case, it is clear why observed and simulated variables (Fig.3 and Fig.4) agree so closely.

Response:

Calibration and validation data were kept separate. We did use some measurements from the POPFULL site for the calibration of the model. These values were, however, not related to the flux data that were only used to validate the model. We changed a sentence in the manuscript to clarify this.

Changes to the manuscript:

Lines 295-296

Comment:

6. p.4028-4029: Please explain the spin-up procedure in more detail. What is the purpose of the different steps required to compute the soil carbon equilibrium? What does "the model was optimized to achieve a soil C equilibrium“ mean in this context? How do you account for the land use history of the two test sites? Differences in previous land use may in part explain differences in simulated and observed carbon sources and sinks.

Response:

We updated the section on the spin-up procedure. A spinup was run to initialize the soil carbon pool. This spinup is performed by running the model with the input data repeatedly, until a soil carbon equilibrium is reached. Because this takes a very long time, a part of this spinup is executed with simplified versions of the model, i.e. teststomate and forcesoil. Teststomate deactivates sechiba, thus only running the daily processes, instead of half-hourly processes, hereby accelerating the model 48 times, reaching a steady state for the non-soil carbon pools. Forcesoil only uses ORCHIDEE's soil carbon module, reaching a steady state for the soil carbon pools. The spinup scenario starts with three times 20 years of the full model, followed by 50 years of teststomate. Then 40 years of the full model, followed by 1000 years of forcesoil, and 260 more years of the full model. This gives a total of 1510 years, of which 360 are run with the full model. The end state of the spinups is then used as initial state for the actual simulations. This has been included in the main text of our manuscript.

Changes to the manuscript:

Lines 263-278

Comment:

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[3] Verlinden M.S., Broeckx L.S., Wei H. and Ceulemans R. (2013) Soil CO2 efflux in a bioenergy plantation with fast-growing Populus trees - influence of former land use, inter-row spacing and genotype. Plant and Soil, 369(1): 631-644.

7. Table1: A more detailed explanation of the variables, equations and their function in the model would be helpful.

Response:

ORCHIDEE is a big leaf model and doesn't simulate individual trees. The functions f_{vol_bm}, f_{bm_vol}, f_{vol_circ}, and f_{circ_vol} are used to partition the biomass into circumference categories and to calculate the biomass of the initial hardwood cuttings from which the plantation is started. The function f_{height_circ} calculates the height from the circumference. This height is used to calculate LAI and roughness height. The roughness height is important in calculating the aerodynamic resistance. We updated the section on the allometric equations to include this.

Changes to the manuscript:

Lines 145-146, 149-154

Comment:

8. Figure 3 and figure 4 show similar information. Does figure 4 provide any additional information?

Response:

We agree that figure 4 (now figure 5), which showed a de-trended version of figure 3 (now figure 4), was partly redundant. We reduced figure 4 (now figure 5) of our manuscript to only show the data for the latent heat flux and highlighted the data points corresponding to the dry spell, which shows the origin of the deviation in latent heat flux simulation, upon request of referee #1 (FIG C).

Changes to the manuscript:

Fig. 5

Comment:

9. Is irrigation possible on SRC plantations?

Response:

Yes. In Southern Europe, SRC is necessarily irrigated to achieve high yields. I mention this in the updated section of the biomass validation, where we validated yield simulations across Europe. This will be further described in the follow up papers where we test different management scenarios. Sprinkler irrigation can be simulated in ORCHIDEE by adding the irrigation as precipitation.

Changes to the manuscript:

Line 248

Comment:

10. ORCHIDEE also simulates nitrogen fertilization. As N2O fluxes are an important element of the overall GHG balance of energy crop cultivation, does this also work for SRC plantations?

Response:

N_2O is an important GHG gas, also for SRC[45]. There is however no N simulation in ORCHIDEE-FM, and therefore also not in ORHCIDEE-SRC. The model assumes a sufficient pool of N in the

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[4] Zona D., Janssens I.A., Aubinet M., Gioli B., Vicca S., Fichot R., Ceulemans R. (2013) Fluxes of the greenhouse gases (CO2, CH4 and N2O) above a short-rotation poplar plantation after conversion from agricultural land. Agricultural and Forest Meteorology, 169: 100-110.

soil and thus, depending on location and soil type, possibly fertilization. But, N loss in an SRC site is minimal, because most of the N is stored in the leaves, which are not harvested during coppicing. Therefore, the majority of the N stays on the site and only minimal N-fertilization is necessary. Moreover, Central Europe has high N deposition rates.

Changes to the manuscript:

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[5] Zona D., Janssens I.A., Verlinden M.S., Broeckx L.S., Cools J., Gioli B., Zaldei A. and Ceulemans R. (2011) Impact of extreme precipitation and water table change on N_2O fluxes in a bio-energy poplar plantation. Biogeosciences Discussions, 8: 2057-2092.

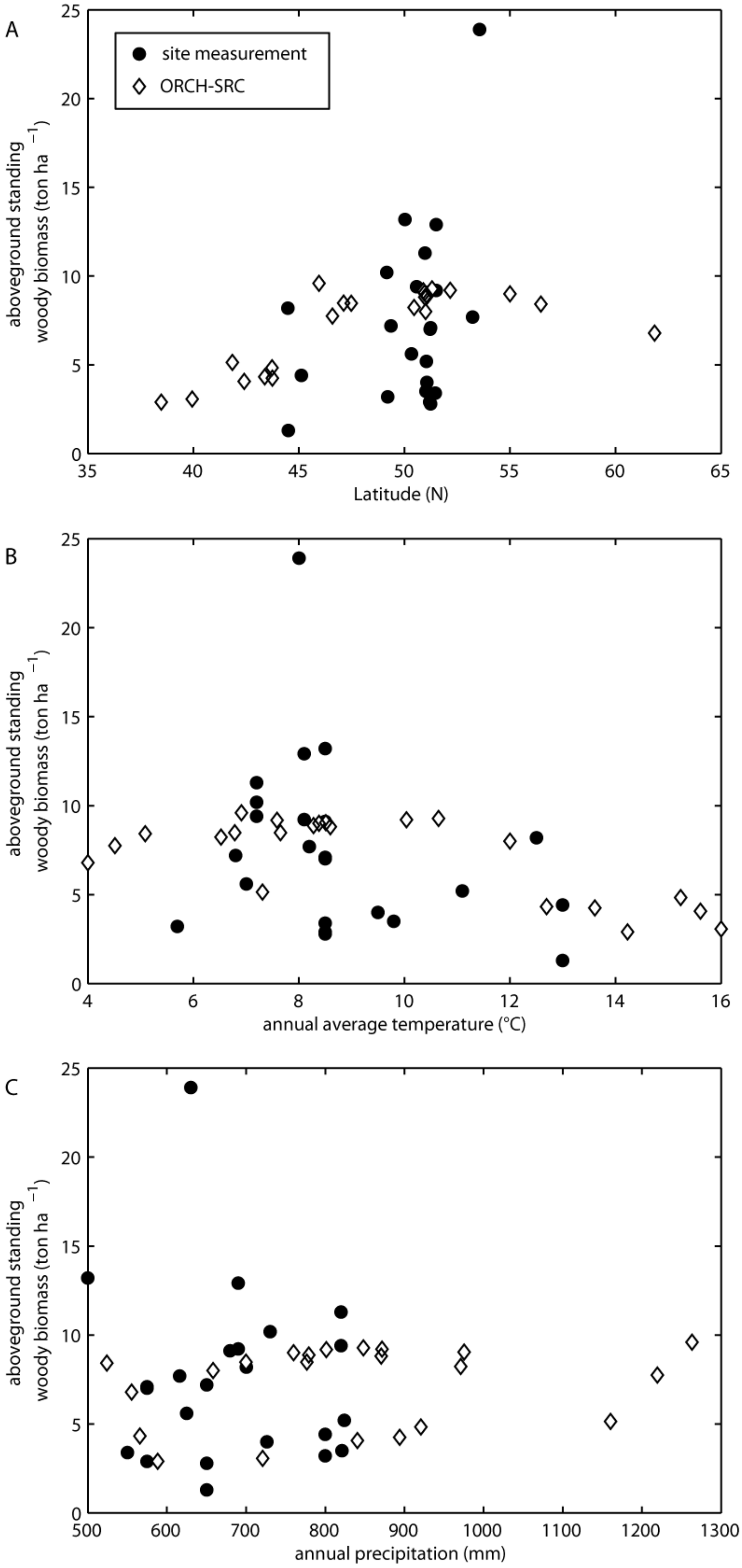

Fig. A: Comparison of aboveground standing woody biomass for ORCHIDEE-SRC simulations (open diamonds) across Europe with site measurements (black circles) across Europe. The biomass is plotted against (A) latitude, (B) annual average temperature and (C) annual precipitation.

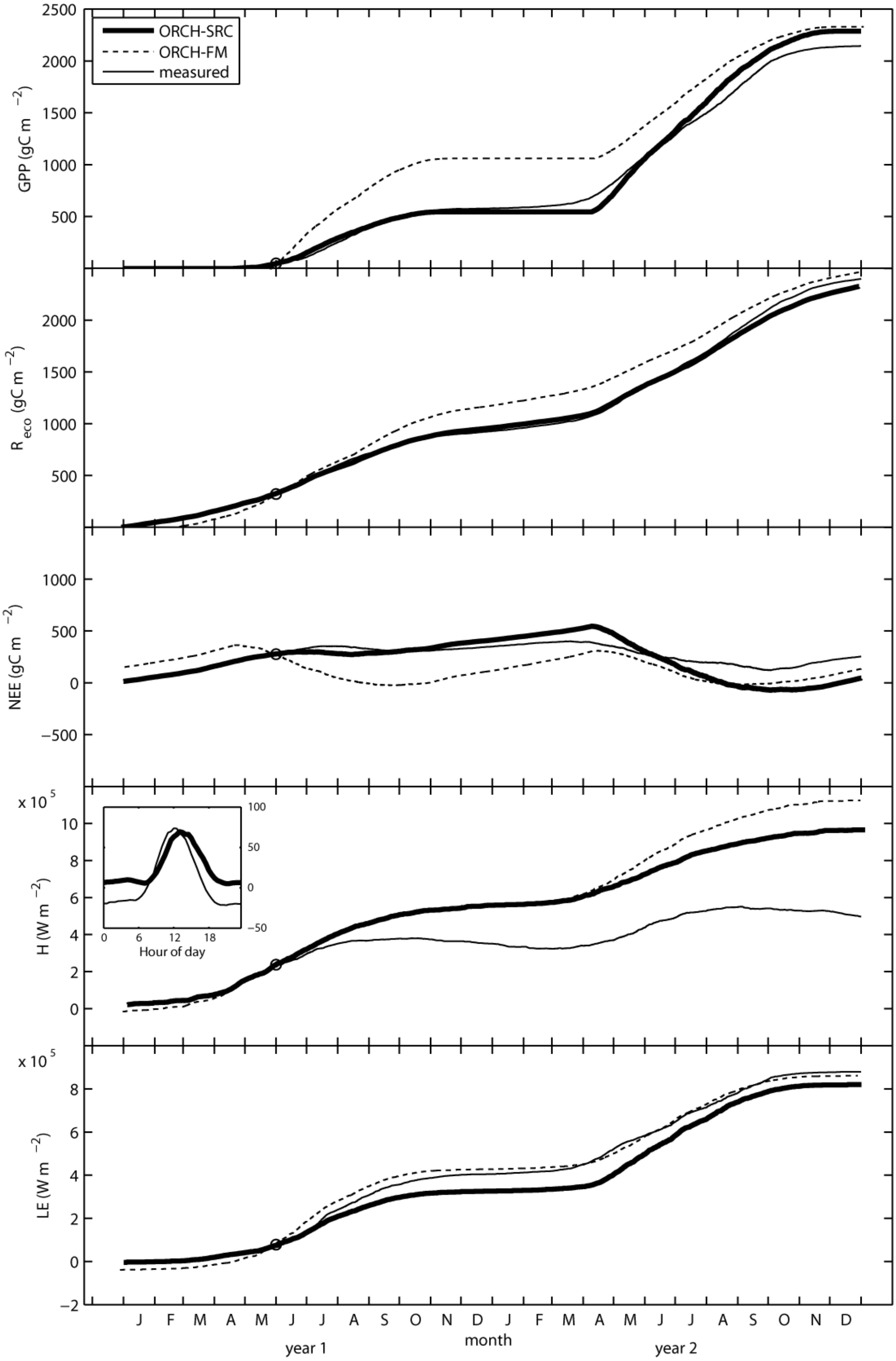

Fig. B: Cumulative fluxes of gross primary production (GPP), ecosystem respiration (Reco), net ecosystem exchange (NEE), sensible heat (H) and latent heat (LE) for the POPFULL site. The insert in the graph for sensible heat flux shows the average diurnal cycle of the sensible heat flux. Thin line:

measurements, fat line: simulations. The thin 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/~MDIwork/eddyproc/). The dashed lines are the model outputs using the standard model ORCHIDEE-FM. The solid thick lines are the model outputs using the modified model ORCHIDEE-SRC. Since there were no flux measurements before June 2010, both simulated and measured values coincide before that date.

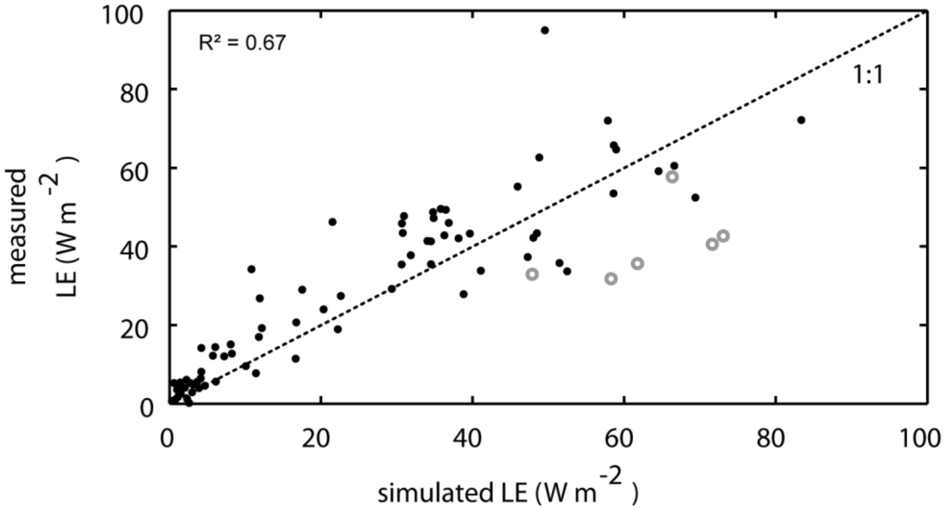

Fig. C: A 1-to-1 comparison of weekly averages of latent heat (LE)for the POPFULL site, between the model outputs and the measured values. The dotted line is the 1 : 1 line. Weeks 18-23 which represent the dry spell are highlighted as grey circles.

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. Modification 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 Belgian, poplar based SRC sites~~.~~, for which multiple measurements and meteorological data was available. Biomass yield data was collected from 23 other sites across Europe and compared to 22 simulations across a comparable geographic range. 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 = 0.0~~81~~78 PCC = 0.91). Also soil temperature and soil moisture are simulated adequately, but due to the simplicity of the soil moisture simulation, there are some discrepancies, which also influence the simulation of the latent heat flux.

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 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. In the future we want to use this model to test a number of management scenarios across Europe to study the variation in the management effects on biomass production and CO_2 uptake. 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 (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). 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 CO_2 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), Net Primary Production (NPP), 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 this extended version can be found at http://forge.ipsl.jussieu.fr/orchidee/browser/perso/toon.degroote/orchidee_FM.

2.2 Model modifications to SRC

2.2.1 Management modifications

A first and essential modification was the ability to simulate multiple rotations, incl. the coppicing of the trees (Appendix A, 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.

$$f_{bm\_vol}\left(\sum \frac{L \cdot circ^{2}}{4\pi}\right) \qquad \text{Eq. (1)}$$

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_{bm_vol} is an allometric function to calculate biomass from volume, as further described in section 2.2.2 and 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 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 (Appendix A, turquoise sections). Half of this C is located in the aboveground 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

Because ORCHIDEE is a big leaf model and does not simulate individual trees, ORCHIDEE-FM uses allometric relations to convert and partition biomass. There are 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; Appendix A, blue sections). The functions f_{vol_bm}, f_{bm_vol}, f_{vol_circ}, and f_{circ_vol} are used to partition the biomass into circumference categories and to calculate the biomass of the initial hardwood cuttings from which the plantation is started. The function f_{height_circ} calculates the height from the circumference. This height is used to calculate LAI and roughness height. The roughness height is important in calculating the aerodynamic resistance. 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 2.3.1).

After coppicing an SRC-tree resprouts as a multi-stemmed tree. This was incorporated into to the model as a second growth modification (Appendix A, 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 (Pontailler 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 (Appendix A, 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.

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 (Appendix A, red sections), and no aboveground sapwood is converted into heartwood (Appendix A, 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 (Appendix A, 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 (Appendix A, 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 (Appendix A, pink sections). Parameters that were in the 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~~Next, 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. Finally, $\rho_{leaf,SW}$ and , $\rho_{leaf,LW}$ are the short wave and long wave leaf albedo. These parameters determine how much of the incoming radiation is absorbed by the leafs and thus influence the energy uptake of the trees.

2.3 Data description

2.3.1 Boom site

The Boom site was poplar-based SRC plantation operating from April 1996 until November 2011 in Boom, near Antwerp, Belgium (51°05’N, 4°22’E; 5 m above sea level). 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, where 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 above ground level. 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) and Dillen et al. (2013).

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 above sea level), 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;2014;2013b). The height of the tower varied between 3 m and 6 m, depending on canopy height. From this tower, CO_2 and H_2O fluxes were measured. Furthermore, leaf phenology was monitored and LAI was regularly measured. Soil temperature and soil moisture were also monitored during 2011. 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;2013a;2014) and the carbon budget was calculated by Verlinden et al. (2013b).

2.3.3 European biomass sites

For the evaluation of aboveground standing woody biomass production across Europe, we used biomass measurements found in Njakou Djomo et al. (2015). From their list of sites, we selected the 23 sites that were not irrigated and had poplar trees (Table 1).

Because meteorological data of sufficient resolution and a detailed site description for these sites were not available, we could not perform a site-by-site comparison. Therefore, we collected meteorological data from 22 different European sites in a similar geographical range on the European Fluxes Database Cluster (http://gaia.agraria.unitus.it/, 1 September 2014) to run our simulations. This way we could compare the range and trend of aboveground woody biomass production along the latitudinal gradient, as well as along the annual precipitation gradient and the average annual temperature gradient,

We selected sites with a public data access and open data use policy, for which data was available for a minimum of five years (Table 1). Using this meteorological data, we ran the model for 20 years, to calculate the mean annual aboveground standing woody biomass production. For these simulations we chose a planting density of 10000 trees ha^{-1} and a rotation cycle of 2 years,

2.4 Simulation setup

Before running the actual simulations, ~~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).~~

a spinup was run to initialize the soil carbon pool for every site.~~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. This spinup is performed by running the model with the available input data repeatedly, until a soil carbon equilibrium is reached. Because this takes a very long time, a part of this spinup is executed with simplified versions of the model, i.e. teststomate and forcesoil. Teststomate deactivates sechiba, thus only running the daily processes, instead of half-hourly processes, hereby accelerating the model 48 times, reaching a steady state for the non-soil carbon pools. Forcesoil only uses the ORCHIDEE's soil carbon module, reaching a steady state for the soil carbon pools.

For this spinup, ~~T~~the model was first run for 20 years, followed by 50 years with teststomate~~a simplified version that only contained the carbon module~~. This was repeated three times. Thereafter, the model was run for 40 years, followed by 1000 years with forcesoil~~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. The end state of the spinups is then used as initial state for the actual simulations.~~ In this spinup, the available meteo data was used throughout the 1510 years.~~

For the simulation of the POPFULL site, the soil fractions where 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

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).

For the POPFULL site, measured eddy covariance fluxes (GPP, R_{eco}, NEE, H and LE) were used to evaluate the model outputs. These data were not related to the data that were used to calibrate the model. 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.

R^2 explains the variance in model performance by comparing it to the data variation. The NRMSE gives a measure for the accumulated model error. The PCC shows how well the data is correlated. While R^2 and PCC give a measure for how well the trends in the data are simulated, NRMSE gives a measure for the total cumulated model error

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

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 & 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. Fig. 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 and soil parameters are given in the sections below.

3.1 Biomass evaluation

3.1.1 Site level

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). 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.

3.1.2 Europe

Since we couldn’t simulate the same sites as we collected measurements for, we compared the average annual aboveground standing woody biomass for the sites across Europe based on their latitude, average annual temperature and average annual precipitation (Fig. 3).

The simulations were within the range of the measured values and followed their general trends. When comparing with latitude, increasing latitudes increase biomass production up to around 55°N. The biomass production of simulations for latitudes above 55°N start declining again, but can’t be compared to measurements, because of lacking data (Fig. 3a). Increasing temperatures have a negative effect on aboveground woody biomass production for both the measurements and the simulations (Fig. 3b). This is probably caused by the negative relation between temperature and precipitation. The simulated aboveground biomass production increases slightly with increasing precipitation (Fig 3c). This trend is also shown by the measured data, except for two high producing sites in the low precipitation range.

Generally, the measured data had a higher spread, which could be explained by variable factors we could not account for in the general modelling approach. Such factors could include genotype selection, weed competition, rotation length, planting density, etc.

3.2 CO_2 flux evaluation

The measured C and energy fluxes at the POPFULL site were compared to the model outputs. Fig. ~~3~~ 4 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. 4~~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 g C m^{-2} week^{-1} in the simulated GPP were caused by this winter CO_2 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. 4~~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~~23.0 Mg C ha^{-1} and 21.4 Mg C ha^{-1} for the model and the measurements, respectively. This difference of 1.~~2~~ 6 Mg C ha^{-1}, represents an overestimation by the model of only ~~5~~7%, well within the uncertainty of eddy covariance-based GPP estimates (Desai et al., 2008;Richardson et al., 2006). ~~Fig. 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 = 0.078~~81~~ PCC = 0.91). The only point of divergence was the dry spell in the summer of the second year. Here, R_{eco} was underestimated, probably because the model is too sensitive to drought. ~~Fig. 4 shows~~

~~this slight underestimation at high R_{eco} values.~~ The accumulated R_{eco} for the first rotation based on observations was 24.0 Mg C ha^{-1}, while the model predicted 23.~~1~~ 3 Mg C ha^{-1}; an underestimation of only ~~4~~3%.

C is taken up by photosynthesis (GPP) and emitted through respiration (R_{eco}). The resulting net flux is NEE. Small errors in GPP and R_{eco} might therefore accumulate in NEE giving it a worse fit. 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~~3.3 Mg ha^{-1}. The model underestimated the C loss to the atmosphere by 3~~4~~9%.

A good fit for GPP and R_{eco} is, however, more important than an accurate simulation of NEE, because they are the real (and large) physical fluxes that occur in the field, and are simulated by the model. Also the soil C loss was simulated adequately. The measured soil C loss was 700 g m^{-2} for the top 15 cm (Verlinden et al., 2013a), while the model predicted a soil C loss of 740 g m^{-2} over the first rotation.

3.3 Water and energy flux evaluation

For H, the cumulative plot (Fig. 4~~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~~36, NRMSE = 0.~~061~~057, PCC = 0.71~~4~~). The error is probably caused by a stable stratification that often develops in dense plantations at night. Because of this stratification the measured sensible heat flux at night is lower than the simulated flux. The averaged diurnal pattern shown in the insert of Fig. 4 clearly shows this discrepancy. The stratification cannot be represented correctly by the calculation of surface drag, in the way it is implemented in ORCHIDEE. This problem did already exist in the model, as described by Krinner et al. (2005).~~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.

During the first growing season, LE increased slower in the model than can be observed in the measured data (R^2 = 0.68~~7~~, NRMSE = 0.055~~6~~, PCC = 0.78; Fig. 4~~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 – 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~~5, as the ~~four overestimated~~six highlighted dots~~ between 60 and 80 W m^{-2}~~ that represent the six dry weeks that are marked in Fig. 6b. At the end of the rotation, this resulted in a cumulative LE of 880 kW m^{-2} for the measurements and 806~~30~~ kW m^{-2} for the model, which is an underestimation of 8~~6~~% by the model.

3.4 Soil variables evaluation

Fig. 6a shows the measured and modeled soil temperature during 2011 for the POPFULL site. This is the only data we had available on soil temperature. This data shows that the soil temperature was simulated very well by our model (R^2 = 0.955, NRMSE = 0.098, PCC = 0.907).

For soil moisture, ORCHIDEE only has two soil compartments, of which one is only present after rainfall (Fig. 6b). We compared the total simulated soil water content to the average measured soil water content of the top 50 cm of soil, which had a reasonable fit (R^2 = 0.976, NRMSE = 0.152, PCC = 0.828). Due to the simplicity of the implementation of soil moisture in ORCHIDEE, the model cannot simulate the level of detail that is shown by the measurements. The model does, however, very clearly show the decline of soil water content during the dry spell, and the replenishment of the top layer with the precipitation after the dry spell.

4 Conclusion

Our validation shows that the modifications ~~The adaptations~~ to the model ORCHIDEE presented in this paper ~~were evaluated using data from two field sites. The simulations show that the model~~ perform~~s~~ well to predict aboveground ~~(~~harvestable~~)~~ woody biomass. Also gross primary production (R^2 = 0.78, NRMSE = 0.064, PCC = 0.89) and ecosystem respiration (R^2 = 0.95, NRMSE = 0.078~~81~~ PCC = 0.91) were simulated very well. Also soil temperature and soil moisture are simulated adequately, but due to the simplicity of the soil moisture simulation, there are some discrepancies, which also influence the simulation of the latent heat flux.~~The modelled soil moisture and latent heat flux differed for certain periods during the year, but~~ The annual latent heat flux was, however, simulated reasonably well ~~simulated~~. ~~For a still unknown reason, the sensible heat seems to be continuously overestimated.~~ Overall the ~~SRC version of the~~ ORCHIDEE-SRC version of the ORCHIDEE model is very well suited to simulate biomass production in SRC plantations.

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6 References

Al Afas, N., Marron, N., Van Dongen, S., Laureysens, I., and Ceulemans, R.: Dynamics of biomass production in a poplar coppice culture over three rotations (11 years), Forest Ecology and Management, 255, 1883-1891, 10.1016/j.foreco.2007.12.010, 2008.

Aylott, M. J., Casella, E., Tubby, I., Street, N. R., Smith, P., and Taylor, G.: Yield and spatial supply of bioenergy poplar and willow short-rotation coppice in the UK, New Phytologist, 178, 358-370, 2008.

Bellassen, V., Le Maire, G., Dhote, J. F., Ciais, P., and Viovy, N.: Modelling forest management within a global vegetation model Part 1: Model structure and general behaviour, Ecological Modelling, 221, 2458-2474, 2010.

Block, R. M. A., Rees, K. C. J., and Knight, J. D.: A review of fine root dynamics in Populus plantations, Agroforest Syst, 67, 73-84, DOI 10.1007/s10457-005-2002-7, 2006.

Broeckx, L. S., Verlinden, M. S., and Ceulemans, R.: Establishment and two-year growth of a bio-energy plantation with fast-growing Populus trees in Flanders (Belgium): Effects of genotype and former land use, Biomass & Bioenergy, 42, 151-163, 2012.

Casella, E., and Ceulemans, R.: Spatial distribution of leaf morphological and physiological characteristics in relation to local radiation regime within the canopies of 3-year-old Populus clones in coppice culture, Tree Physiology, 22, 1277-1288, 2002.

Choisnel, E.: Le bilan d'énergie et le bilan hydrique du sol, La Météorologie, 6, 103-133, 1977.

Coleman, M. D., Dickson, R. E., and Isebrands, J. G.: Contrasting fine-root production, survival and soil CO2 efflux in pine and poplar plantations, Plant Soil, 225, 129-139, Doi 10.1023/A:1026564228951, 2000.

DEFRA: Growing short rotation coppice - Best practice guidelines for applicants to Defra’s energy crops scheme, Department for Environment, Food and Rural Affairs, London, UK, 2004.

Desai, A. R., Richardson, A. D., Moffat, A. M., Kattge, J., Hollinger, D. Y., Barr, A., Falge, E., Noormets, A., Papale, D., Reichstein, M., and Stauch, V. J.: Cross-site evaluation of eddy covariance GPP and RE decomposition techniques, Agr Forest Meteorol, 148, 821-838, DOI 10.1016/j.agrformet.2007.11.012, 2008.

Dickmann, D., and Stuart, K. W.: The culture of poplars in eastern North America, Dept. of Forestry, Michigan State University, East Lansing, Mich. and Dansville, 1983.

Dillen, S. Y., Vanbeveren, S., al Afas, N., Laureysens, I., Croes, S., and Ceulemans, R.: Biomass production in a 15-year-old poplar short-rotation coppice culture in Belgium, Aspects of applied biology, 112, 99-106, 2011.

Dillen, S. Y., Djomo, S. N., Al Afas, N., Vanbeveren, S., and Ceulemans, R.: Biomass yield and energy balance of a short-rotation poplar coppice with multiple clones on degraded land during 16 years, Biomass & Bioenergy, 56, 157-165, 2013.

Ducoudre, N. I., Laval, K., and Perrier, A.: Sechiba, a New Set of Parameterizations of the Hydrologic Exchanges at the Land Atmosphere Interface within the Lmd Atmospheric General-Circulation Model, Journal of Climate, 6, 248-273, 1993.

EC: Communication from the commision - Europe 2020 - A strategy for smart, sustainable and inclusive growth. COM 2010;2020. Final (03/03/2010), European Commission, Brussels, 2010.

Hansen, E. A.: Poplar Woody Biomass Yields - a Look to the Future, Biomass & Bioenergy, 1, 1-7, 1991.

Herve, C., and Ceulemans, R.: Short-rotation coppiced vs non-coppiced poplar: A comparative study at two different field sites, Biomass & Bioenergy, 11, 139-150, Doi 10.1016/0961-9534(96)00028-1, 1996.

Krinner, G., Viovy, N., de Noblet-Ducoudre, N., Ogee, J., Polcher, J., Friedlingstein, P., Ciais, P., Sitch, S., and Prentice, I. C.: A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, Global Biogeochemical Cycles, 19, GB1015, 2005.

Laureysens, I., Deraedt, W., Indeherberge, T., and Ceulemans, R.: Population dynamics in a 6-year old coppice culture of poplar. I. Clonal differences in stool mortality, shoot dynamics and shoot diameter distribution in relation to biomass production, Biomass & Bioenergy, 24, 81-95, 2003.

Muhle Larsen, C.: Considérations sur l'amélioration du genre Populus et spécialement sur la section Aigeiros63-2b/9, 1963.

Njakou Djomo, S., Ac, A., Zenone, T., De Groote, T., Bergante, S., Facciotto, G., Sixto, H., Ciria Ciria, P., Weger, J., and Ceulemans, R.: Energy performances of intensive and extensive short rotation cropping systems for woody biomass production in the EU, Renewable and Sustainable Energy Reviews, 41, 845-854, http://dx.doi.org/10.1016/j.rser.2014.08.058, 2015.

Pontailler, J. Y., Ceulemans, R., and Guittet, J.: Biomass yield of poplar after five 2-year coppice rotations, Forestry, 72, 157-163, 1999.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grunwald, T., Havrankova, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J. M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., and Valentini, R.: On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm, Global Change Biology, 11, 1424-1439, 2005.

Richardson, A. D., Hollinger, D. Y., Burba, G. G., Davis, K. J., Flanagan, L. B., Katul, G. G., Munger, J. W., Ricciuto, D. M., Stoy, P. C., Suyker, A. E., Verma, S. B., and Wofsy, S. C.: A multi-site analysis of random error in tower-based measurements of carbon and energy fluxes, Agr Forest Meteorol, 136, 1-18, DOI 10.1016/j.agrformet.2006.01.007, 2006.

Verlinden, M. S., Broeckx, L. S., Wei, H., and Ceulemans, R.: Soil CO2 efflux in a bioenergy plantation with fast-growing Populus trees - influence of former land use, inter-row spacing and genotype, Plant Soil, 369, 631-644, DOI 10.1007/s11104-013-1604-5, 2013a.

Verlinden, M. S., Broeckx, L. S., Zona, D., Berhongaray, G., De Groote, T., Camino Serrano, M., Janssens, I. A., and Ceulemans, R.: Net ecosystem production and carbon balance of an SRC poplar plantation during its first rotation, Biomass and Bioenergy, 56, 412-422, 10.1016/j.biombioe.2013.05.033, 2013b.

Zervos, A., Lins, C., and Tesnière, L.: EU Roadmap - Mapping Renewable Energy Pathways towards 2020, European Renewable Energy Council, Brussels, Belgium, 104, 2011.

Zona, D., Janssens, I. A., Aubinet, M., Gioli, B., Vicca, S., Fichot, R., and Ceulemans, R.: Fluxes of the greenhouse gases (CO2, CH4 and N2O) above a short-rotation poplar plantation after conversion from agricultural land, Agr Forest Meteorol, 169, 100-110, DOI 10.1016/j.agrformet.2012.10.008, 2013a.

Zona, D., Janssens, I. A., Gioli, B., Jungkunst, H. F., Serrano, M. C., and Ceulemans, R.: N2O fluxes of a bio-energy poplar plantation during a two years rotation period, GCB Bioenergy, 5, 536-547, 10.1111/gcbb.12019, 2013b.

Zona, D., Gioli, B., Fares, S., De Groote, T., Pilegaard, K., Ibrom, A., and Ceulemans, R.: Environmental controls on ozone fluxes in a poplar plantation in Western Europe, Environmental Pollution, 184, 201-210, 2014.

7 Tables and Figures

7.1 Tables

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
$f_{vol\_bm} \rightarrow volume = \frac{biomass}{density}$	density	1.25e5	g C m^{-3}
$f_{bm\_vol} \rightarrow biomass = volume \cdot density$			
$f_{vol\_circ} \rightarrow volume = \sum \frac{a \cdot \left(\frac{circumference}{\pi} \right)^{b}}{density}$	density	1.25e5	g C m^{-3}
	a	0.033	
	b	2.6	
$f_{circ\_vol} \rightarrow circumference = \pi \cdot \left(\frac{volume \cdot density}{a} \right)^{1/b}$			
$f_{height\_circ} \rightarrow height = a \cdot circumference^{b}$	a	17.2684	
	b	0.6791	

Table 2: Parameter values that where 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, $\rho_{leaf,SW}$ = short wave leaf albedo, $\rho_{leaf,LW}$ = long wave leaf albedo.

Parameter	Unit	ORCHIDEE PFT 6	ORCHIDEE-SRC
LAI_{max}	m^2 m^{-2}	4.5	2.5
$V_{c,max}$	µmol m^{-2} s^{-1}	55	130
J_{max}	µmol m^{-2} s^{-1}	70	180
H_{root}		0.8	1.5
$\rho_{leaf,SW}$		0.06	0.20
$\rho_{leaf,LW}$		0.22	0.30

Table 3: Biomass validation site info for the simulated sites, acquired from the European Fluxes Database Cluster (http://gaia.agraria.unitus.it/, 1 September 2014) and the measured sites, acquired from (Njakou Djomo et al., 2015).

Simulations						Measurements					
Country	Site name	Latitude	Longitude	Annual temp °C	Annual precip mm	Country	Site name	Latitude	Longitude	Annual temp °C	Annual precip mm
PT	Mitra IV (Tojal)	38.48 N	8.02 W	14.2	588	IT	Caramagna piemonte	44.47 N	7.44 E	12.5	700
ES	Las Majadas del Tietar	39.94 N	5.77 W	16.1	721	IT	Lombriasco	44.51 N	7.38 E	13.0	650
IT	Collelongo	41.85 N	13.59 E	7.3	1160	CZ	Nová Olešná	49.17 N	15.16 E	7.2	730
IT	Roccarespampani 1	42.41 N	11.93 E	15.6	840	CZ	Bystřice	49.21 N	12.48 E	5.7	800
FR	Mauzac	43.39 N	1.29 E	12.7	566	CZ	Smilkov	49.36 N	14.36 E	6.8	650
IT	San Rossore	43.73 N	10.28 E	15.2	921	CZ	Rosice	50.03 N	15.42 E	8.5	500
FR	Puechabon	43.74 N	3.6 E	13.6	894	DE	Arnsfeld	50.34 N	13.06 E	7.0	625
IT	Lavarone	45.96 N	11.28 E	6.9	1263	DE	Großschirma	50.57 N	13.17 E	7.2	820
IT	Renon	46.59 N	11.43 E	4.5	1219	DE	Krummenhennersdorf	50.98 N	13.36 E	7.2	820
AT	Neustift	47.12 N	11.32 E	6.8	700	BE	Zwijnaarde	51.02 N	3.43 E	9.8	821
CZ	Laegern	47.48 N	8.37 E	7.7	777	BE	Boom	51.05 N	4.22 E	11.1	824
DE	Wetzstein	50.45 N	11.46 E	6.5	971	BE	Lochristi	51.06 N	3.51 E	9.5	726
DE	Klingenberg	50.89 N	13.52 E	7.6	801	DE	Commichau	51.08 N	12.50 E	8.5	680
DE	Grillenburg	50.95 N	13.51 E	8.5	975	DE	Skäßchen	51.20 N	13.35 E	8.5	575
DE	Tharandt	50.96 N	13.57 E	8.6	871	DE	Großthiemig	51.22 N	13.4 E	8.5	575
DE	Hainich	51.08 N	10.45 E	8.3	779	DE	Thammenhain	51.25 N	12.51 E	8.5	575
BE	Brasschaat	51.31 N	4.52 E	10.6	848	DE	Nochten	51.25 N	14.36 E	8.5	650
UK	Pang/Lambourne forest	51.45 N	1.27 W	12.3	658	DE	Vetschau	51.46 N	14.04 E	8.5	550
NL	Loobos	52.17 N	5.74 E	10.0	872	DE	Methau I	51.50 N	12.51 E	8.1	690
DK	Soroe	55.49 N	11.64 E	8.4	760	DE	Methau II	51.50 N	12.51 E	8.1	690
RU	Fyodorovskoye	56.46 N	32.92 E	5.1	524	DE	Kuhstorf	53.23 N	11.15 E	8.2	616
FI	Hyytiälä	61.85 N	24.3 E	4.1	555	DE	Laage	53.55 N	12.20 E	8.0	630

7.2 Figures

Fig. 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; Bx = aboveground woody biomass production of rotation x.

Fig. 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×B), *P. trichocarpa* × *P. deltoides* (T×D), *P. trichocarpa* (T), *P. deltoides* × *P. nigra* (D×N), *P. deltoides* × *P. trichocarpa* (D×T), *P. nigra* (N), *P. canadensis* (C), *P. deltoides* × (*P. trichocarpa* × *P. deltoides*) (D×(T×D)), *P. trichocarpa* × *P. maximowiczii* (T×M).

Fig. 3: Comparison of aboveground standing woody biomass for ORCHIDEE-SRC simulations (open diamonds) across Europe with site measurements (black circles) across Europe. The biomass is plotted against (A) latitude, (B) annual average temperature and (C) annual precipitation.

Fig. 4~~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 insert in the graph for sensible heat flux shows the average diurnal cycle of the sensible heat flux. The thin~~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/~MDIwork/eddyproc/). The dashed line are the model outputs using the standard model ORCHIDEE-FM. The solid thick lines are the model outputs using the modified model ORCHIDEE-SRC. Since there were no flux measurements before June 2010, both simulated and measured values coincide before that date.

Fig. ~~4~~5: 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. Weeks 18-23 which represent the dry spell are highlighted as grey circles.

Fig. 6: A comparison of modelled and measured soil state variables for 2011 at the POPFULL site. (A) shows the daily average soil temperature simulated (fat) and measured (thin). (B) shows the soil water content. The gray area represents the measured range of soil water content values for the top 50 cm of the soil. The dotted line is the soil water content of the lower soil water compartment of the model and the solid line is the total soil water content of the upper and lower soil water compartments.

Fig. 1

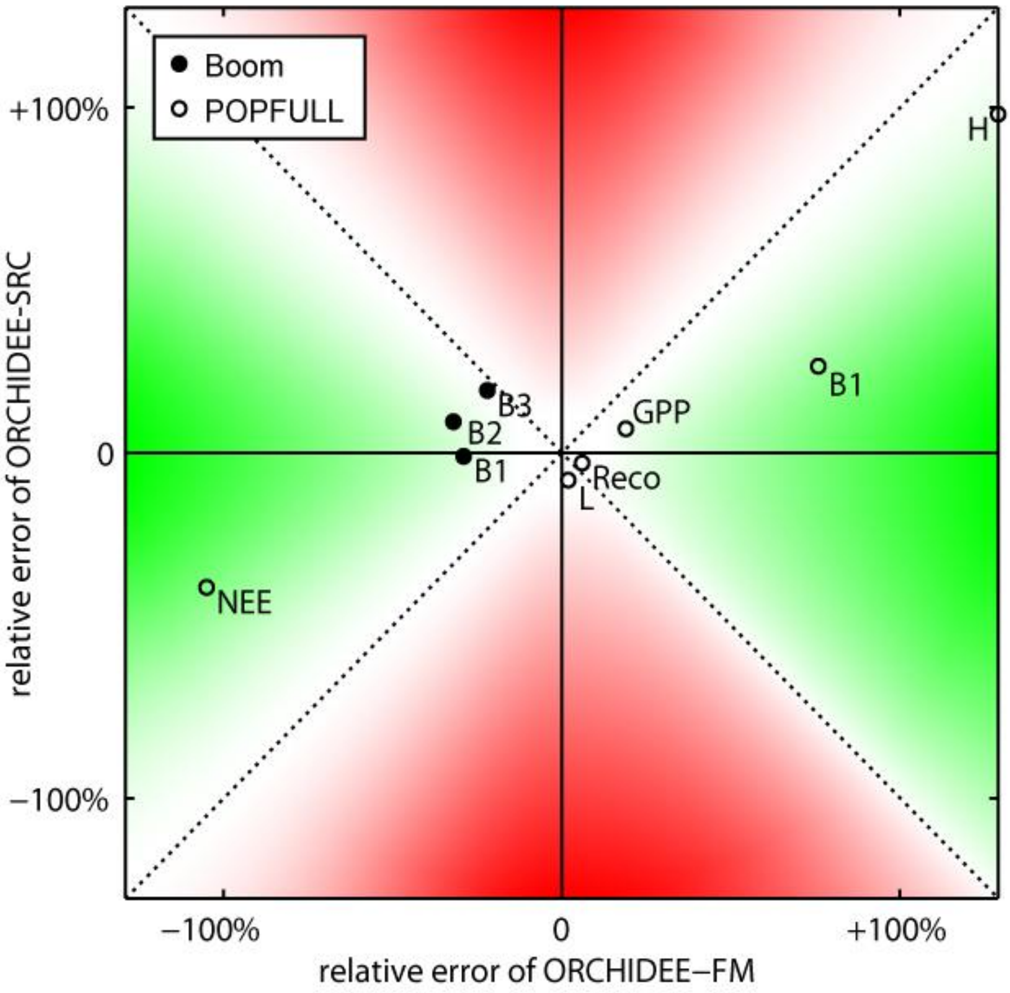

● Boom
○ POPFULL
+100%
0
−100%
relative error of ORCHIDEE-SRC
−100%
0
+100%
relative error of ORCHIDEE−FM
H
B1
B3
B2
B1
GPP
Reco
L
NEE

Fig. 2

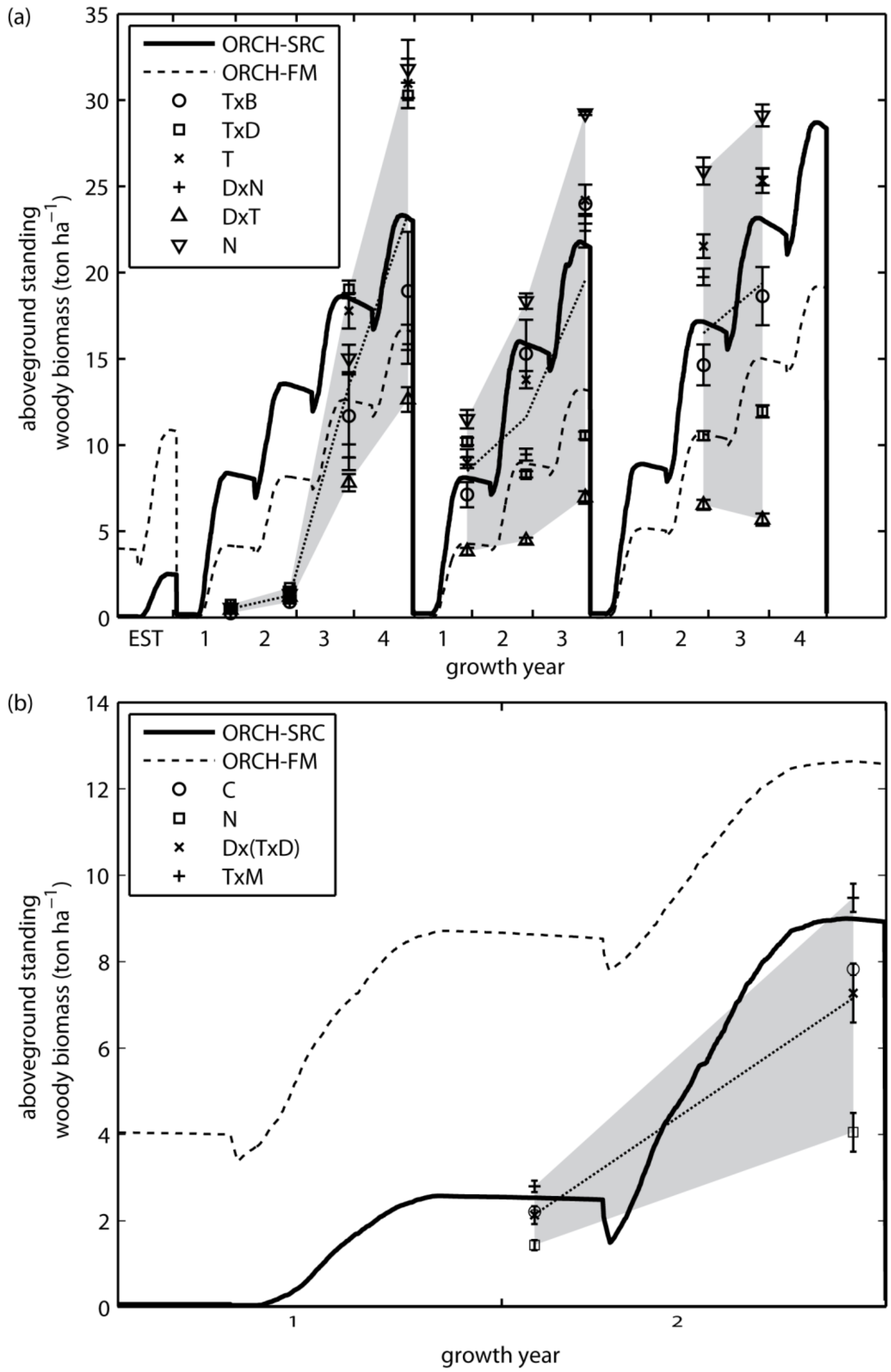

(a)
ORCH-SRC
ORCH-FM
TxB
TxD
T
DxN
DxT
N
aboveground standing woody biomass (ton ha^{-1})
growth year
EST
1
2
3
4
0
5
10
15
20
25
30
35
(b)
ORCH-SRC
ORCH-FM
C
N
Dx(TxD)
TxM
aboveground standing woody biomass (ton ha^{-1})
growth year
0
2
4
6
8
10
12
14
1
2

Fig. 3

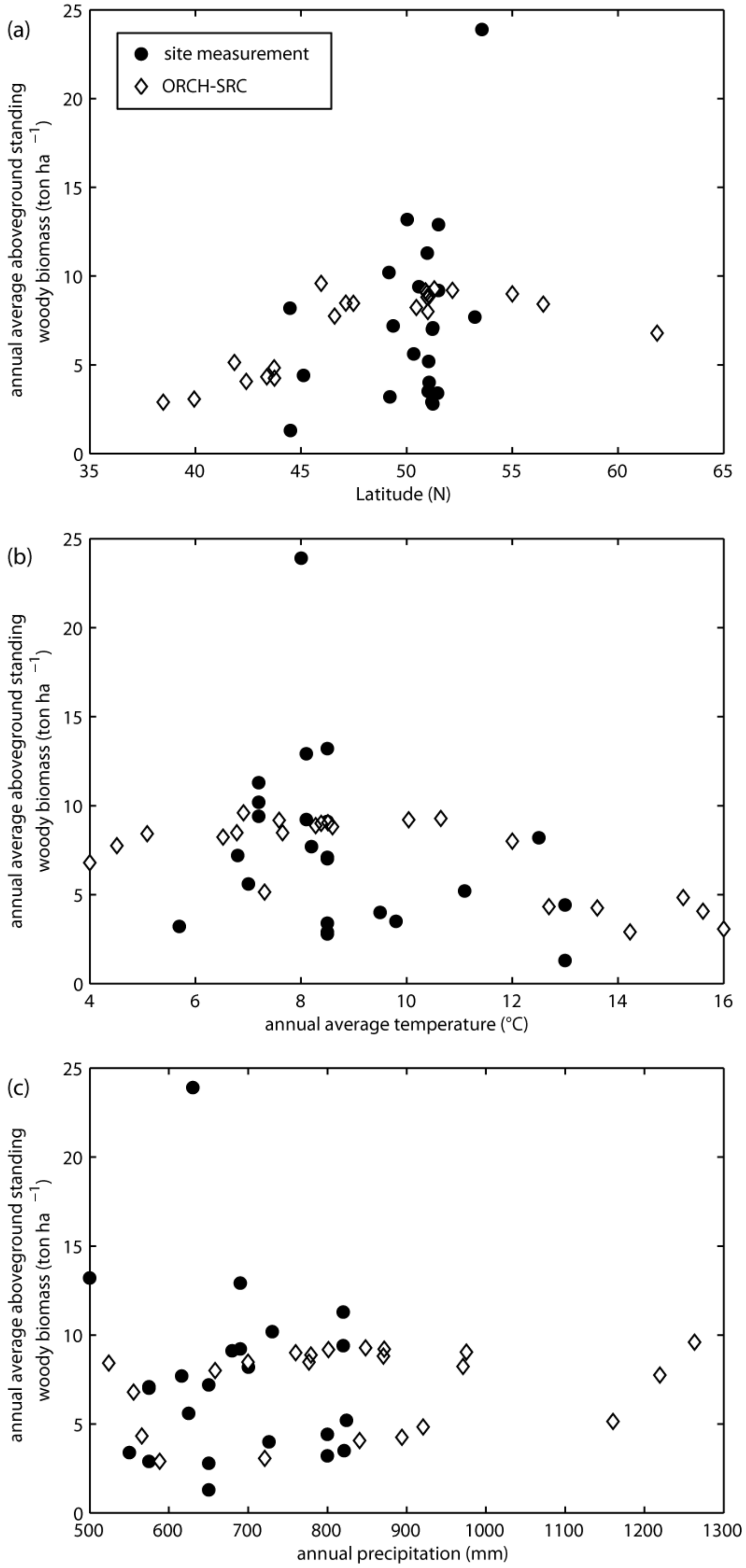

(a)
site measurement
ORCH-SRC
annual average aboveground standing woody biomass (ton ha $^{-1}$)
Latitude (N)
35
40
45
50
55
60
65
0
5
10
15
20
25
(b)
annual average temperature (°C)
4
6
8
10
12
14
16
(c)
annual precipitation (mm)
500
600
700
800
900
1000
1100
1200
1300

Fig. 4

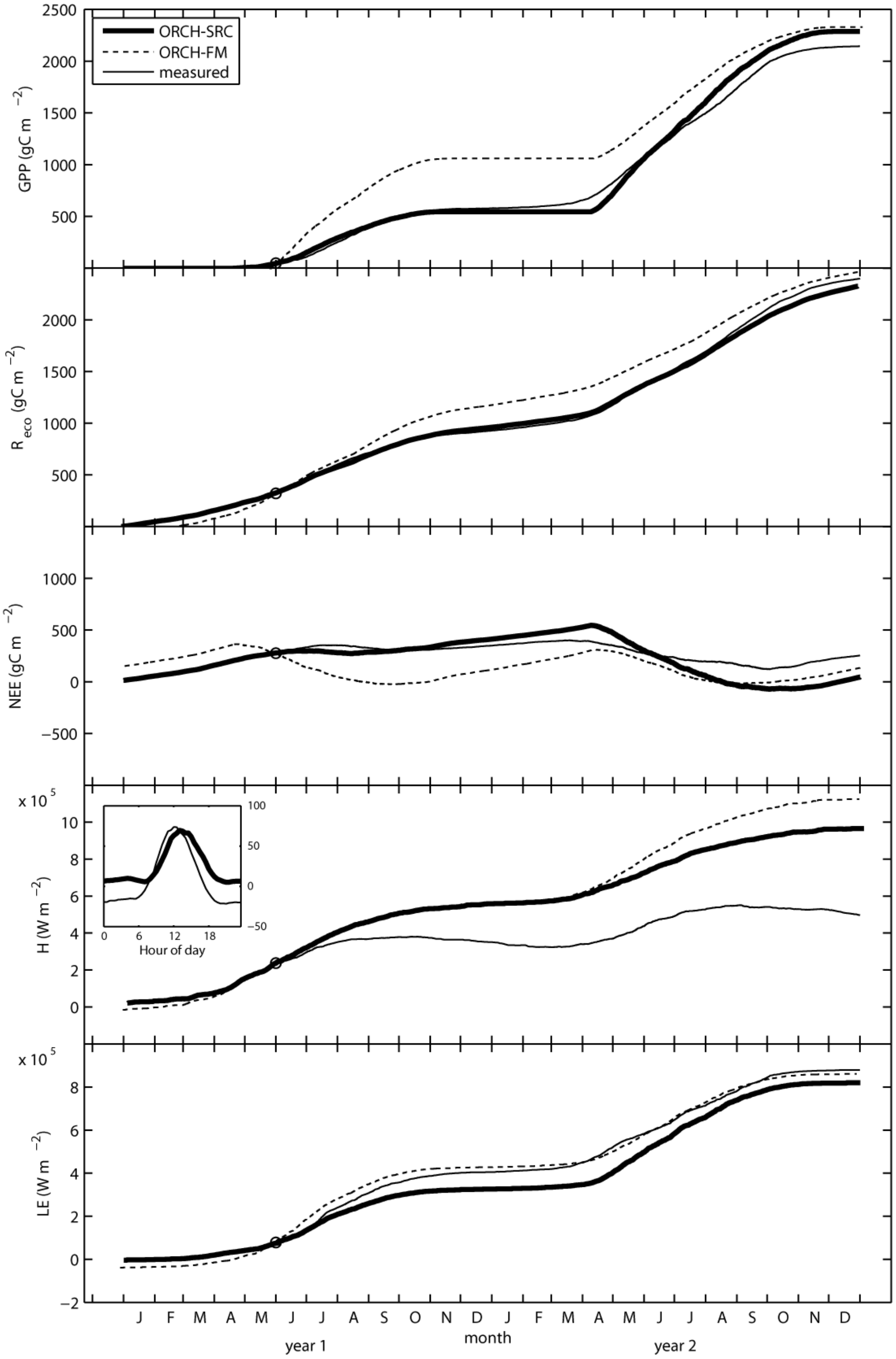
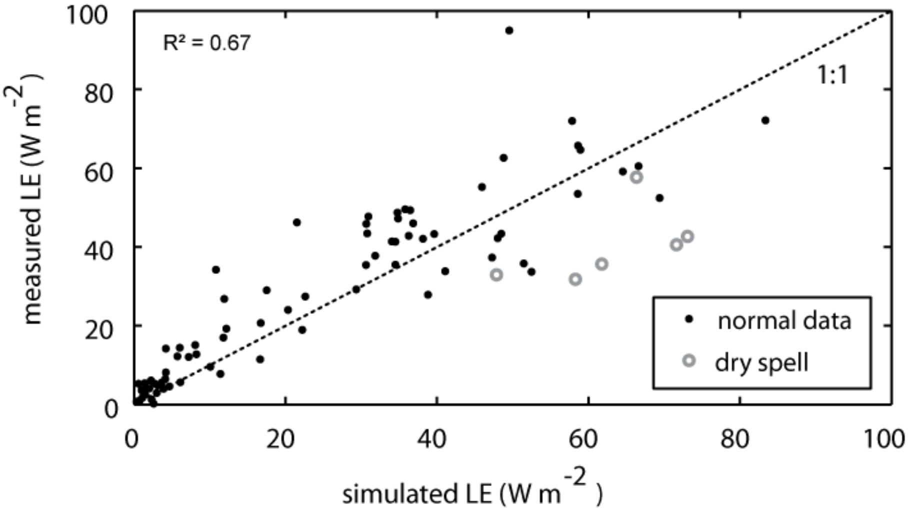
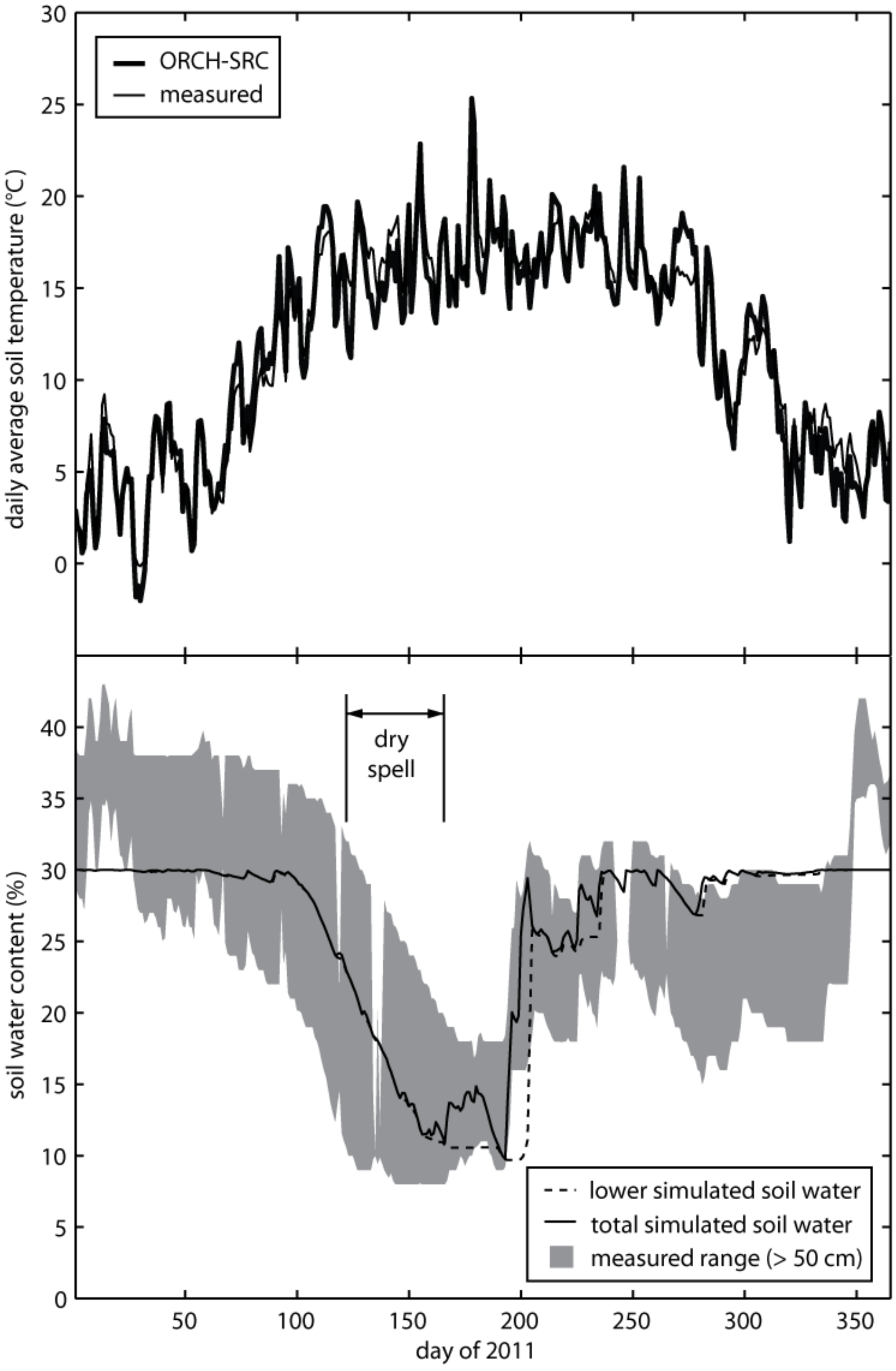

2500
2000
1500
1000
500
GPP (gC m −2)
ORCH-SRC
ORCH-FM
measured
2000
1500
1000
500
R eco (gC m −2)
1000
500
0
−500
NEE (gC m −2)
x 10 5
10
8
6
4
2
0
H (W m −2)
100
50
0
−50
0
6
12
18
Hour of day
x 10 5
8
6
4
2
0
−2
LE (W m −2)
J
F
M
A
M
J
J
A
S
O
N
D
J
F
M
A
M
J
J
A
S
O
N
D
year 1
month
year 2

Fig. 5


R² = 0.67
1:1
normal data
dry spell
measured LE (W m^{-2})
simulated LE (W m^{-2})
0
20
40
60
80
100
0
20
40
60
80
100

673 Fig. 6


ORCH-SRC
measured
daily average soil temperature (°C)
30
25
20
15
10
5
0
dry
spell
soil water content (%)
40
35
30
25
20
15
10
5
0
lower simulated soil water
total simulated soil water
measured range (> 50 cm)
50
100
150
200
250
300
350
day of 2011

674