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Description and evaluation of the process-based forest model 4C v2.2 at four European forest sites

Petra Lasch-Born et al.

Correspondence to: Petra Lasch-Born (lasch@pik-potsdam.de), and Felicitas Suckow (suckow@pik-potsdam.de)

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S1 OVERVIEW ABOUT 4C APPLICATIONS

Table S1 Applications of the model 4C

Publication	Region	Analysis	Results
Lasch et al., 2002	Pine stand in Brandenburg, several 24 pine, spruce, oak and beech stands in Germany	Sensitivity study regarding climate and growth analysis under climate change	Water limitation effects for forest growth in German temperate forests are important and an increasing direct effect of rising temperatures at higher elevation sites is shown.
Gerstengarbe et al., 2003	Brandenburg/ Germany	Effects of climate change on carbon budget and water balance of forests in Brandenburg using 461 forest stands and one climate scenario	The effects of climate change were stronger for the water balance than for the carbon budget due to the assumed climate scenario.
Badeck et al., 2005	Management unit in Brandenburg/ Germany	Application of adaptive forest management strategies and climate scenarios to a management unit in Brandenburg	- The effect of choosing alternative treatment programs on harvested wood volumes can be smaller or higher than the climate change impact. - Both the alternative treatment programs and climate change increased the volume of harvested timber.
Fürstenau et al., 2007	Management unit in Brandenburg/ Germany	Evaluation of alternative management strategies at the forest management unit level under current climate and under transient climate change conditions over a planning period of 100 years. Application	- Climate change increases carbon sequestration and income from timber production due to increased stand productivity. - Forest manager in public-owned forests or a private forest owner

Publication	Region	Analysis	Results
		of a multi-criteria analysis method	would prefer a management strategy with an intermediate thinning intensity and a high share of pine stands
Lasch et al., 2007	3 Level II ICP Forest plots in Brandenburg, Lower Saxony and Bavaria	Application of climate scenarios with temperature increase and varying precipitation changes to analyse carbon budget of the forest stands.	Model simulated an increase in carbon stock of stem biomass, deadwood and soil.
Meiwes et al., 2007	21 Level II plots in Bavaria, Brandenburg and Lower Saxony Germany	Modeling of the carbon budgets	Models are suitable instruments for the analysis of the observation data from the monitoring plots. The combination of monitoring and modelling allows the evaluation of effects of climate change and forest management.
Seidl et al., 2008	Forest management unit in Carinthia, southern Austria	Application of different management strategies under current climate and transient climate change and comparison with the model PICUS	– A transition to continuous cover forestry increased C storage in all climate scenarios compared to the approximately balanced C budget under the age class system. – With regard to climate change impacts both models agreed on distinct effects on productivity but lower sensitivity of C stocks due to compensation from respiration and adaptive harvest levels
Wechsung et al., 2009	Agricultural land in the 5 Federal states of East Germany	Model based yield estimation of aspen short rotation coppice SRC under climate	Yields of fast growing aspen in SRC are expected to increase under the presumed changes of climate also on sandy soils

Publication	Region	Analysis	Results
		change	with low water holding capacity even when neglecting the beneficial effect of higher CO_2.
Kint et al., 2009	Galgenberg forest in the Netherlands	Investigation how conversion management of a Scots pine *Pinus sylvestris* L. stand towards a mixed oak-birch stand would affect stand structural development and hence biodiversity and productivity in the long term.	The optimal conversion regime – in which both stand productivity and biodiversity objectives can be combined – implies thinning from above, pine tree retention, and cutting cycles of 6 years.
Kollas et al., 2009	Agricultural land in Germany	Exploration the actual and future energy potential of short-rotation cop scenarios.	– If 4 m ha were used as SRC, between 415 and 522 PJ a-1 of primary energy could be produced in the scenario periods 2041-2060. – SRC can deliver a substantial contribution to the primary energy production in 2060.
Lasch et al., 2009	Mixed Scots pine-oak stands in Brandenburg Germany	Analysis of carbon and water budget with various management strategies and under climate change; comparison with the model BWINPro	4C allows the analysis of various ecosystem functions and the evaluation of management strategies regarding these functions.
Lasch et al., 2010	Agricultural land in the 5 Federal states of East Germany	Estimation of the potential woody biomass yield of SRC plantations with aspen on suitable land in Eastern Germany under climate change and evaluation how aspen SRC plantation affects groundwater recharge and the impacts of land use change on the soil	Aspen SRC plantations are a suitable contribution to regional CO_2 mitigation and carbon sequestration under possible change of climate, but that negative impacts on the regional water budget are possible.

Publication	Region	Analysis	Results
		properties.	
Reyer et al., 2010	Mixed Douglas fir- beech stands in Germany and in the Netherlands	Climate change effects on the inter-specific competition in a managed Douglas-fir/beech mixed forest.	Simulated climate change does not substantially alter the interaction of the two species. The concept of complementary water use highlights the importance of mixed forest for climate change adaptation.
Gutsch et al., 2011	Mixed oak-pine stand in Brandenburg/ Germany	Analysis of different management scenarios under climate change	– The analysis of variance in the growth related model outputs showed an increase of climate related uncertainty of forest growth with increasing climate warming. – The increase of climate induced uncertainty is much higher from 2 to 3 K than from 0 to 2 K.
Borys et al., 2013	Four beech forests of a management unit in Thuringia	Analysis of carbon budget of the long-term experimental stands using a wood product model	– The impact of management on the carbon budgets is more determining than the impact of the selected climate scenarios. – The unmanaged experimental site under the 3K-scenario stores the highest amount of total carbon.
van Oijen et al., 2013	Twelve sites, from Austria, Belgium, Estonia and Finland.	Evaluation how Bayesian calibration BC, Bayesian model comparison BMC and Bayesian model averaging BMA can help to assess the uncertainty of model predictions.	– BC reduced uncertainties strongly in all but the most complex model. – BMC using NFI- and PSP-data identified the 4C model, which is of moderate complexity but

Publication	Region	Analysis	Results
			mechanistic, as the most plausible forest model after calibration.
Stojanović et al., 2014	Nine European beech forest sites in Serbia	Integration of stakeholder preferences, experts' opinion and forest growth modelling for climate and management scenario assessments	– Forest management together with stakeholder preferences will play much bigger role in providing of better support for ecosystem service in comparison to climate conditions – frequent felling operations provide better result than less frequent operations for the same amount of harvested wood.
Reyer et al., 2014	132 typical forest sites of important European tree species in ten environmental zones in Europe.	Projection of forest productivity changes under different climate change scenarios at a large number of sites in Europe with a stand-scale process-based model.	– Future forest productivity will be affected by climate change and these effects depend strongly on the climate scenario used and the persistence of CO_2 effects. Productivity increases in Northern Europe, increases or decreases in Central Europe, and decreases in Southern Europe.
Borys et al., 2015	Management unit in Thuringia Buchfahrt	Economic analysis of the beech stands of the considered management unit	– The study shows that from an economic point of view it is often more appropriate to abandon the usual thinning management of beech stands with heavy thinning from above in favour of management fostering stronger carbon storage. – The increase in carbon storage in the forest by medium thinning from

Publication	Region	Analysis	Results
			below and no management was, however, associated with additional costs or lower revenues of 112 € and 123 € per additional ton of carbon stored respectively.
Gutsch et al., 2015a	Agriculture and Forestry in Germany	Assessment of the uncertainty caused by climate change effects in the potential supply of biomass available for energy production.	In five federal states the climate scenarios lead to decreasing yields of energy maize and winter wheat. Impacts of climate scenarios on forest yields are mainly positive and show both positive and negative effects on yields of SRC.
Gutsch et al., 2015b	Two mono-species Scots pine stands and two mixed Scots pine-oak stands in the lowlands of northeastern Germany.	Analysis of two water uptake approaches an empirical and a more process-based one in Scots pine and Scots pine-Sessile oak stands.	Accurate projections of future forest productivity depend largely on the realistic representation of root water uptake in forest model simulations. Three different measured parameters transpiration, soil water content, tree rings did not allow a superior approach to each other.
Schelhaas et al., 2015	Europe	The data from Reyer et al. 2014 was used to scale the future productivity changes in EFISCEN.	The European forest system is very inert and it takes a long time to influence the species distribution by replacing species after final felling. By 2070, on average about 36 % of the area expected to have decreased species suitability will have changed species following business as usual management. Alternative management, consisting of shorter rotations for those species and species

Publication	Region	Analysis	Results
			planting based on expected trends, will have increased this species transition to 40 %.
Lasch-Born et al., 2015	Forested area in Germany	How do changes in net primary production and timber production interact with changes in the water budget under climate change? What are the possible risks of fire danger or pest outbreaks?	The dryer water-limited low elevated regions reaching from southwestern to northeastern Germany will benefit less from the assumed climate change than regions in the Northwest and forest sites at higher altitudes, which are mainly temperature limited.
Borys et al., 2016	Forest management unit in Thuringia Buchfahrt	Assessment how much carbon C is currently stored in a forest district and how the carbon stocks will develop up to the year 2099 with a changing climate and under various management regimes including no management, with different assumptions about carbon dioxide CO_2 fertilization effects.	Climate change affects carbon sequestration. The no management strategy sequestered the highest amount of carbon which was greater than the management regimes. In the model, the possible fertilization effect of CO_2 is an important factor. However, forest management remains the determining factor in this forest district.
Gutsch et al., 2016	Forest area Germany	This study aims to derive simple models from 4C simulations with low data requirements which allow calculation of NPP and analysis of climate impacts using many climate scenarios at a large amount of sites.	The fitted regression functions showed a reasonable fit to measured NPP datasets. Temperature increase of up to 3 K leads to positive effects on NPP. In water-limited regions, this positive effect is dependent on the length of drought periods.
Reyer et al., 2016	Two NFI sites each from Austria,	This paper aims to integrate parameter	If a key objective in climate change

Publication	**Region**	**Analysis**	**Results**
	Belgium, Estonia and Finland	uncertainty into simulations of climate change impacts on forest net primary productivity NPP. Application of either prior uncalibrated or posterior calibrated using Bayesian calibration parameter variations to express parameter uncertainty.	impact research is to quantify uncertainty, parameter uncertainty as a major factor driving the degree of uncertainty of projections should be included.
Suckow et al., 2016	Scots pine stand Zotino Siberia, Russia	Analysis of impacts of climate change on a pine forest stand in Central Siberia to assess benefits and risks for such forests in the future.	The analysis confirms increasing productivity of the boreal pine stand but also highlights increasing drought stress and risks from abiotic disturbances which could cancel out productivity gains.
Horemans et al., 2017	FLUXNET sites: Soroe Denmark, Vielsalm Belgium and Collelongo Italy.	The performance of two global dynamic vegetation models, i.e. CARAIB and ISBACC, and one stand-scale forest model, i.e. 4C, was compared to long-term observed net ecosystem carbon exchange NEE time series from eddy covariance monitoring stations at three old-grown European beech Fagus sylvatica L. forest stands	– The most important errors for all three models occurred at the edges of the observed NEE distribution and the model errors were correlated with environmental variables on a daily scale – Models should be evaluated across multiple sites, preferably using multiple evaluation methods, to identify processes that request reconsideration.
Gutsch et al., 2018	Germany’s forests, NFI data BWI[3]	Quantification o the effects of two alternative management scenarios and climate impacts on forest variables indicative of ecosystem services related to	– Northeastern and western forest regions are more suitable to provide timber while minimizing the negative impacts on remaining ecosystem services whereas southern and central

Publication	Region	Analysis	Results
		timber, habitat, water, and carbon.	forest regions are more suitable to fulfil ‘habitat’ and ‘carbon’ services. – The results provide the base for future forest management optimizations at the regional scale in order to maximize ecosystem services and forest ecosystem sustainability at the national scale.
Kollas et al., 2018	Scots pine stand in Berlin Germany	Estimation of mistletoe-induced losses in timber yield applying the process-based forest growth model 4C.	Simulations showed that the amended forest growth model 4C depicts well the BAI growth pattern during >100 years and also quantifies well the mistletoe-induced growth reductions in Scots pine stands.
Yousefpour et al., 2018	Forest stands in 18 European countries	Simulation of European commercial forests’ growth conditions and coupled it with an optimization algorithm to simulate the implementation of Climate Smart Forestry for 18 European countries encompassing 68.3 million ha of forest 42.4% of total EU-28 forest area	A European Climate Smart Forestry CSF policy could sequester 7.3–11.1 billion tons of carbon, projected to be worth 103 to 141 billion euros in the 21st century. An efficient CSF policy would allocate carbon sequestration to European countries with a lower wood price, lower labour costs, high harvest costs, or a mixture thereof to increase its economic efficiency.
Lasch-Born et al., 2018	Germany’s forests	Ongoing climate change affects growth and increases biotic and abiotic threats to Germany’s forests. How do these risks develop through the mid-century under a	All indicators showed higher risks for the scenario time period compared to the recent time period, except the late frost risk indicators, if averaged over all

Publication	Region	Analysis	Results
		variety of climate change scenarios using 4C?	climate scenarios. The late frost risk for beech and oaks decreased for the main forest sites.
Bugmann et al., 2019	Scots pine stand Peitz Germany 4C	Evaluation 15 dynamic vegetation models DVMs regarding their sensitivity to different formulations of tree mortality under different degrees of climate change.	1 Mortality is one of the most uncertain processes when it comes to assessing forest response to climate change, and 2 more data and a better process understanding of tree mortality are needed to improve the robustness of simulated future forest dynamics. Our study highlights that comparing several alternative mortality formulations in DVMs provides valuable insights into the effects of process uncertainties on simulated future forest dynamics.

S2 FOREST GROWTH

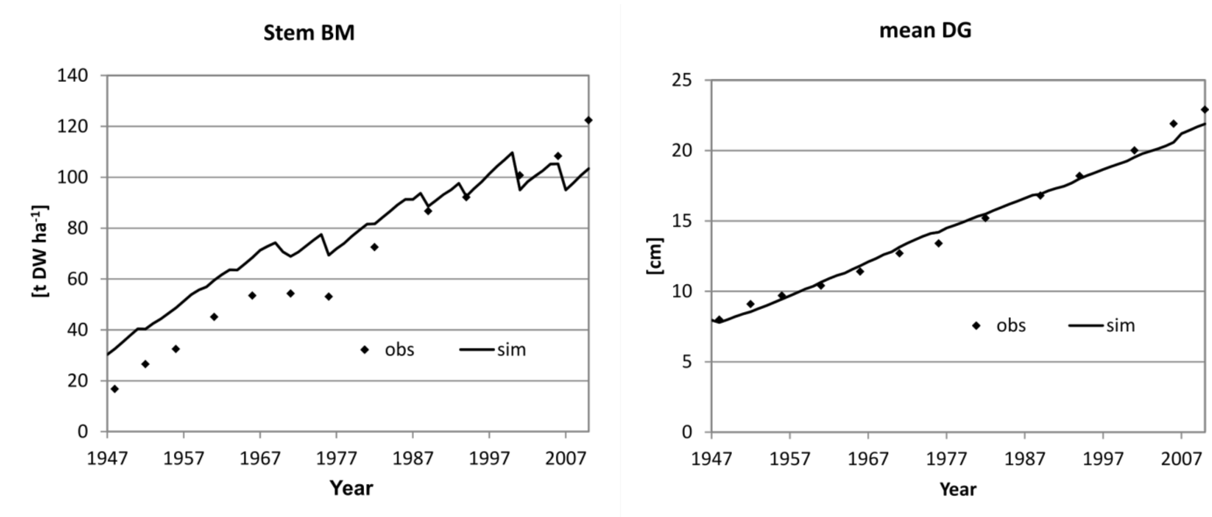

Figure S1 Simulated sim and observed obs DG and stem biomass BM for Peitz. The plots show the time series.

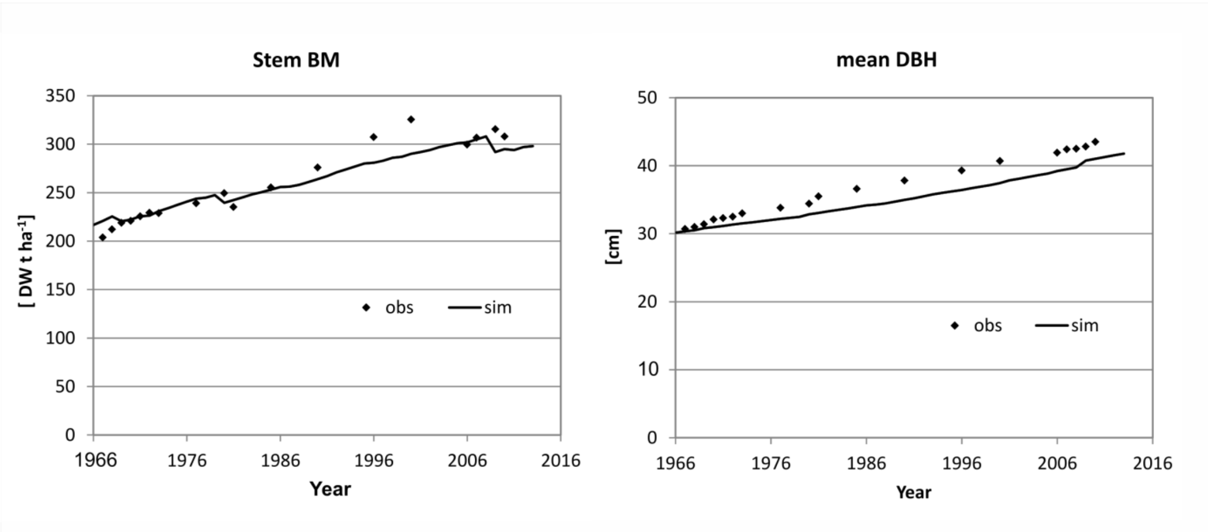

Figure S2 Simulated sim and observed obs DBH and stem biomass BM for Solling. The plots show the time series.

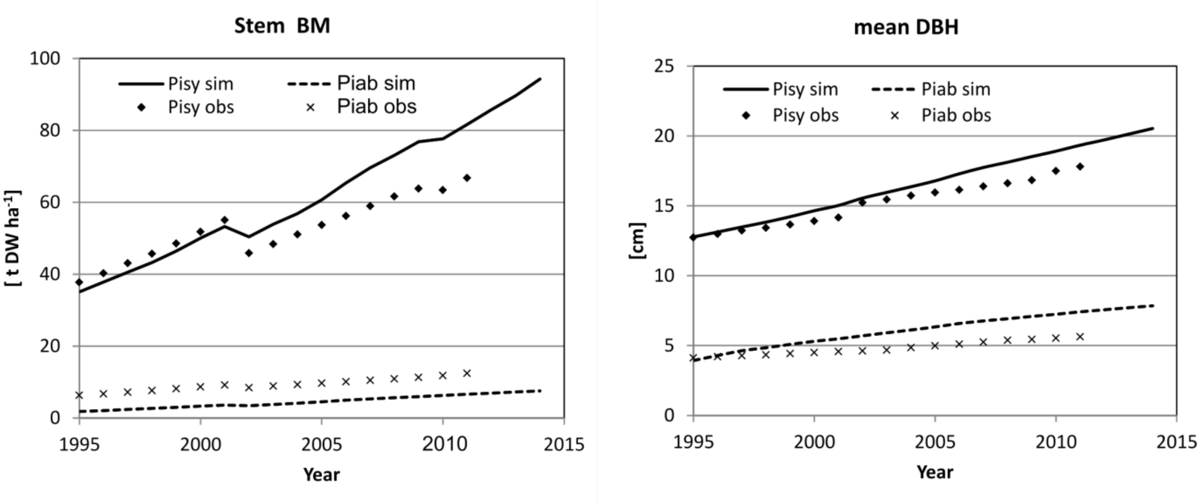

Figure S3 Simulated sim and observed obs DBH and stem biomass BM for Hyytiälä Pisy – pine, Piab – spruce. The plots show the time series.

S3 FLUXES

S3.1 Sorø

S3.1.1 Graphical analysis daily data Sorø

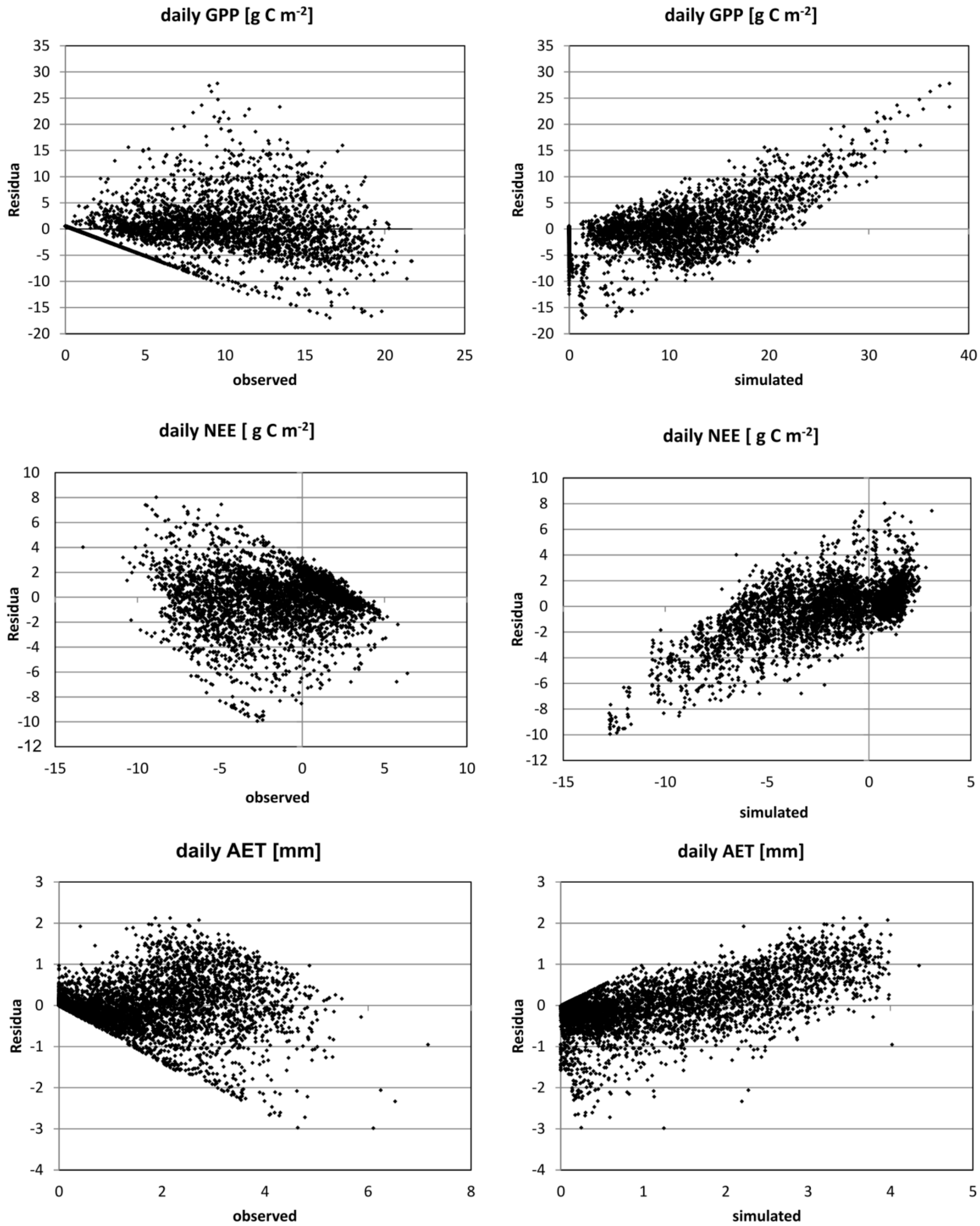

Figure S4 Residual plots of GPP, NEE and AET for Sorø; 1996-2012

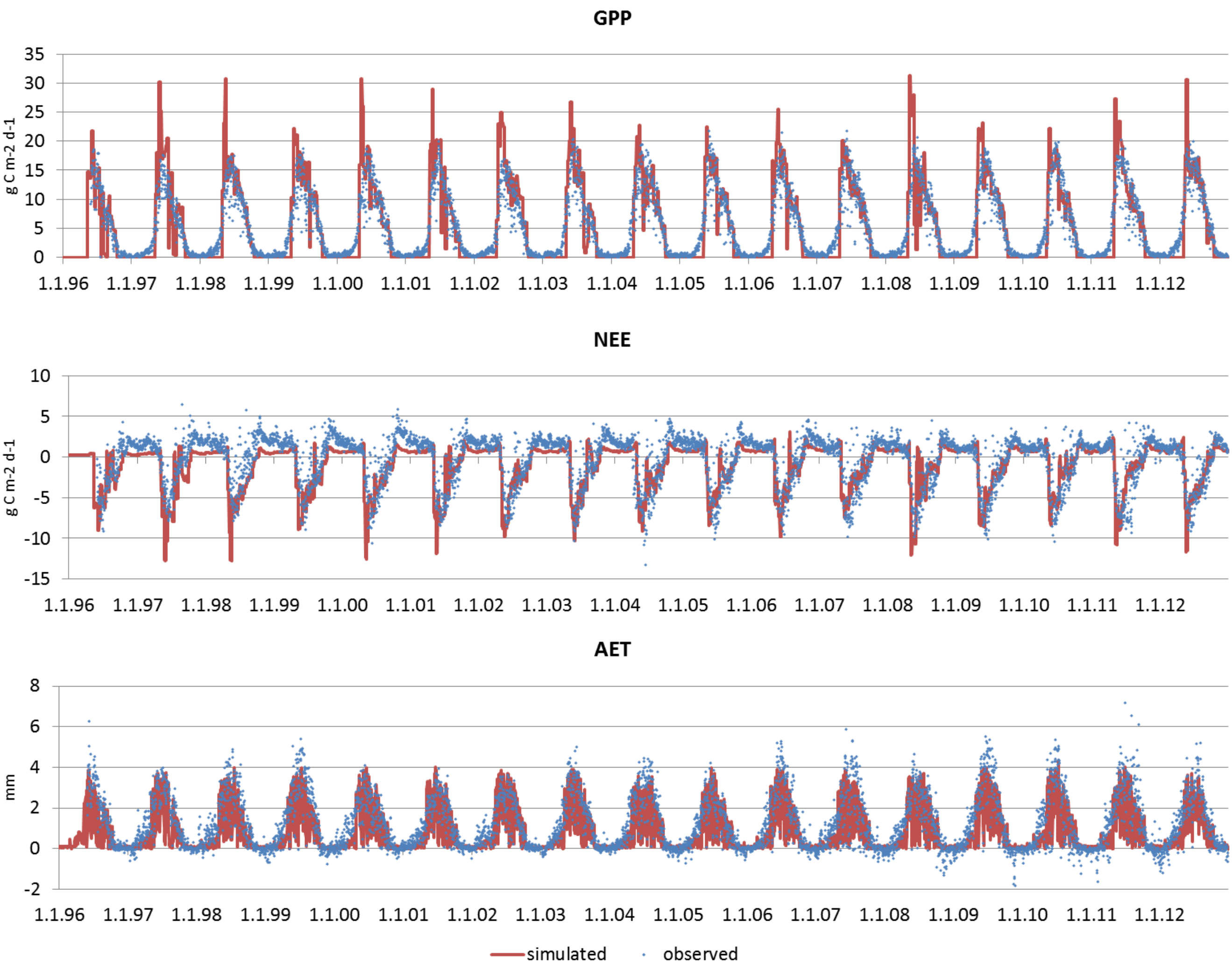

Figure S5 Time series of GPP, NEE, and AET for Sorø; 1996-2012

S3.1.2 Graphical analysis monthly data Sorø

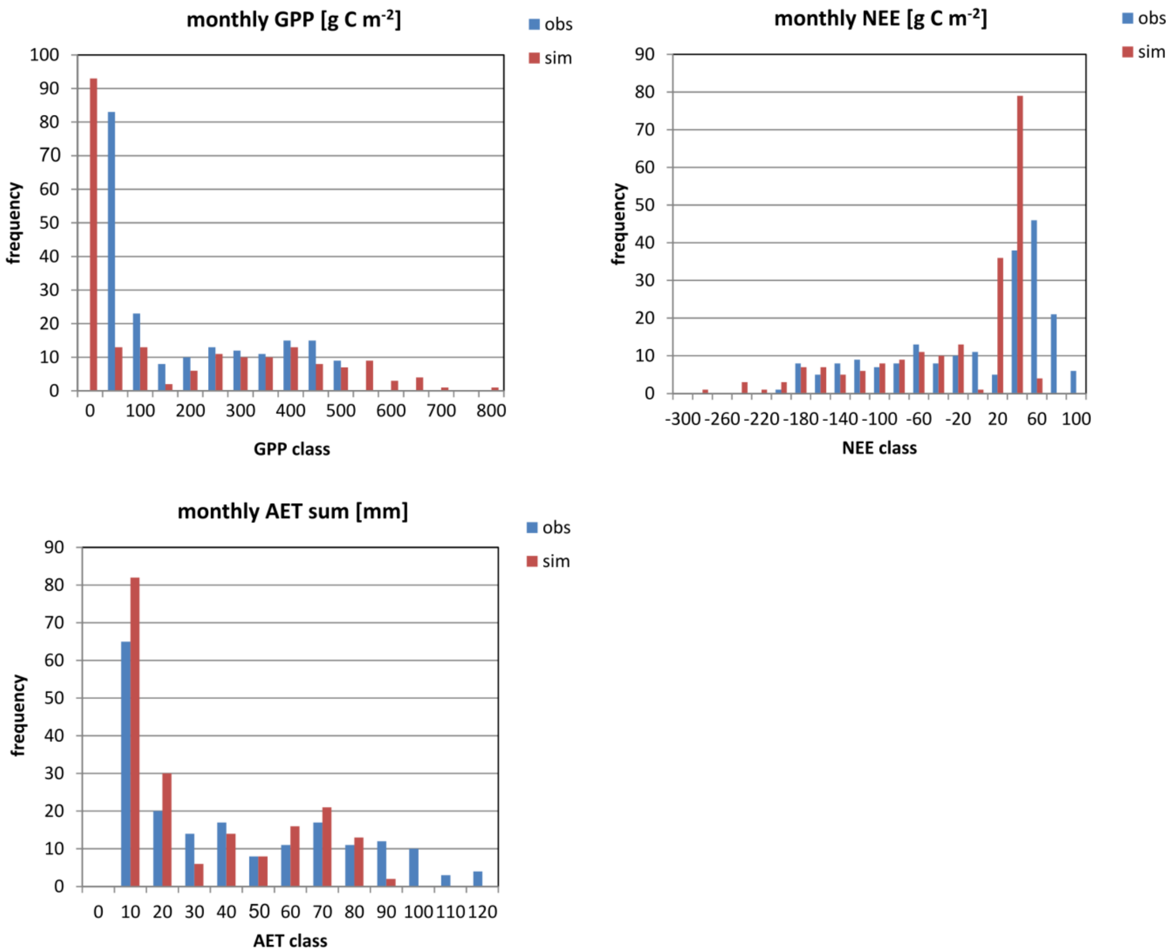

Figure S6 Frequency plots of monthly data of GPP, NEE and AET for Sorø; 1996-2012

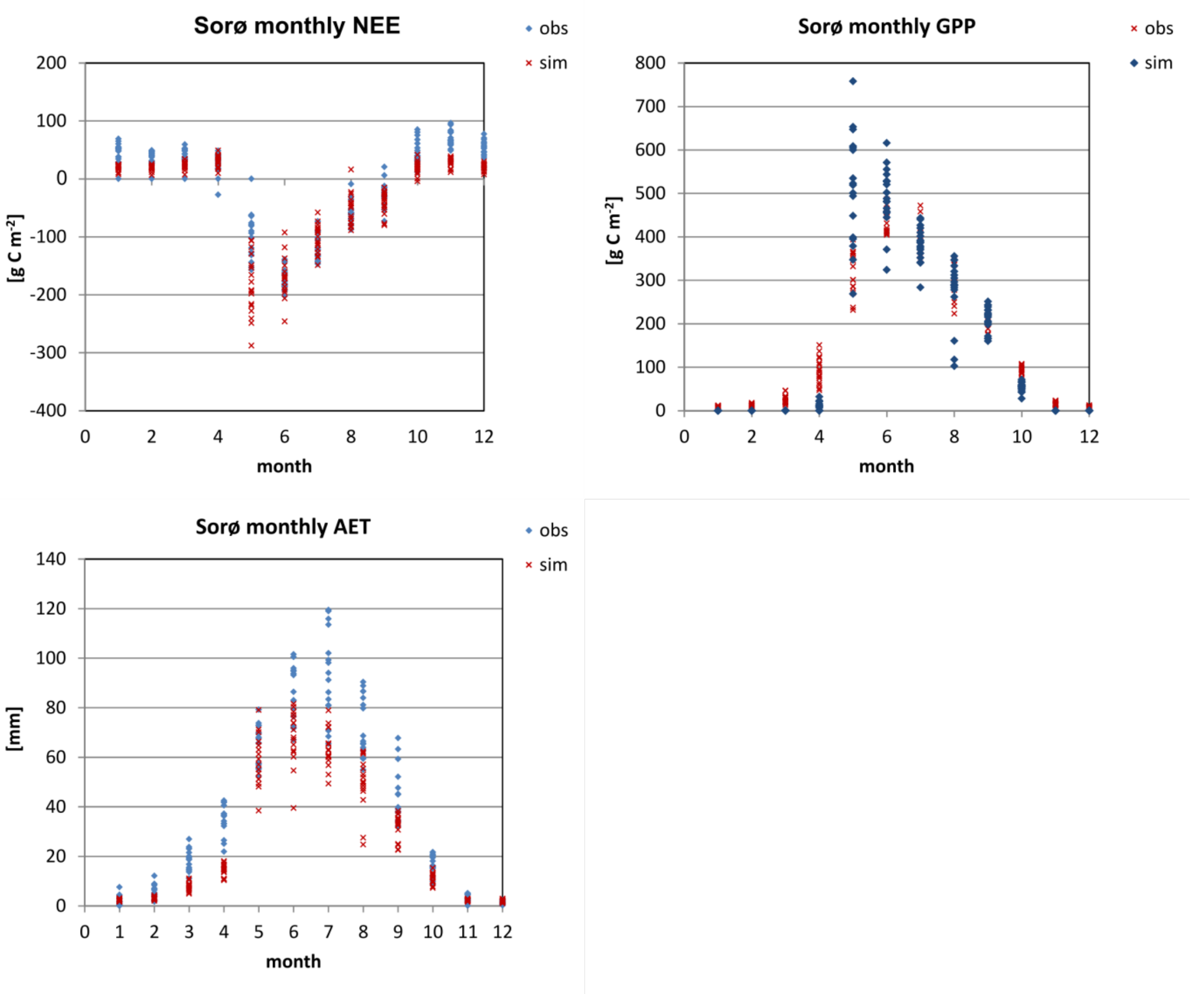

Figure S7 Seasonal cycle of monthly GPP, NEE and AET values obs - observed, sim - simulated for Sorø

S3.2 Hyytiälä

S3.2.1 Graphical analysis daily data Hyytiälä

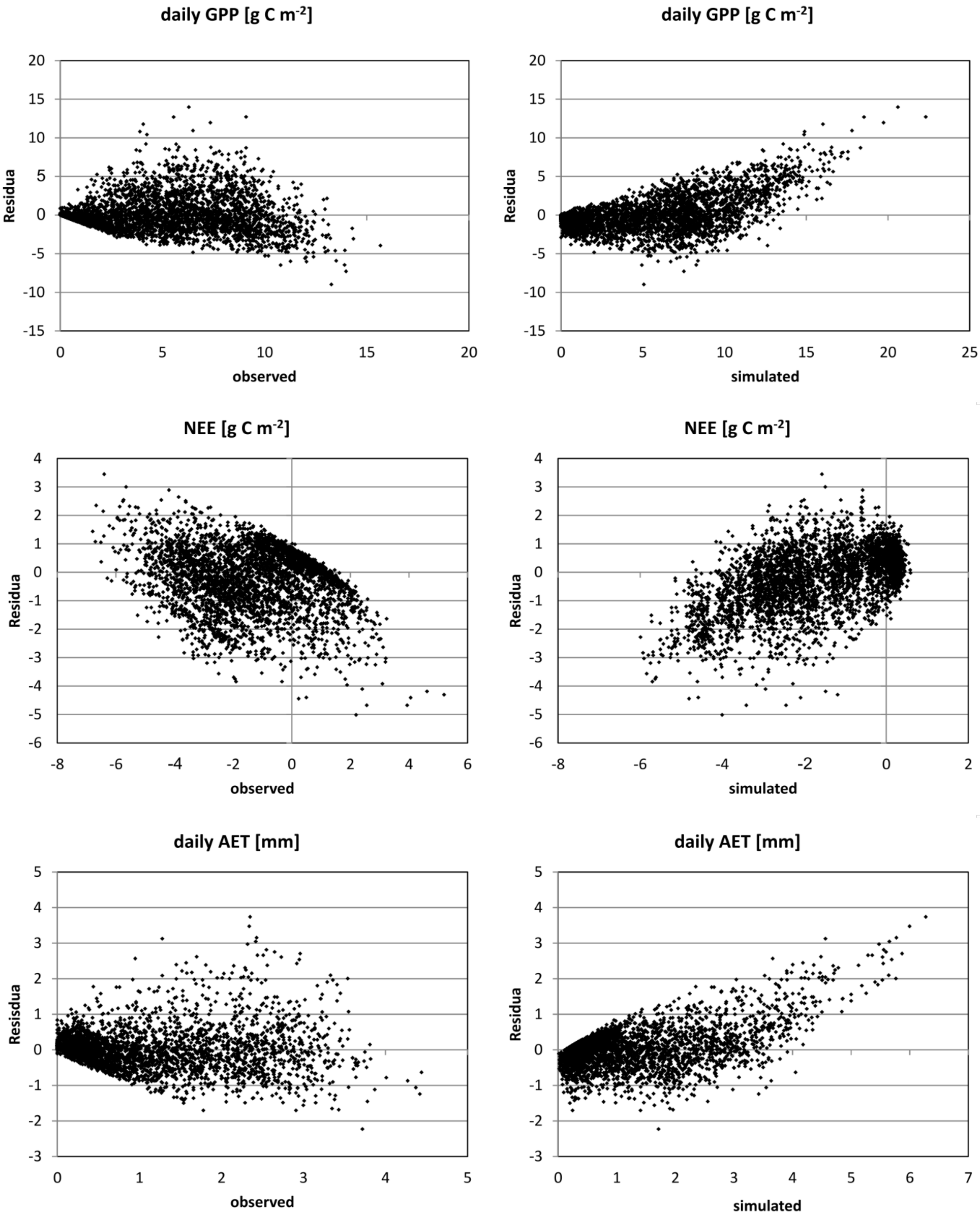

Figure S8 Residual plots of GPP, NEE and AET for Hyytiälä; 1996-2014

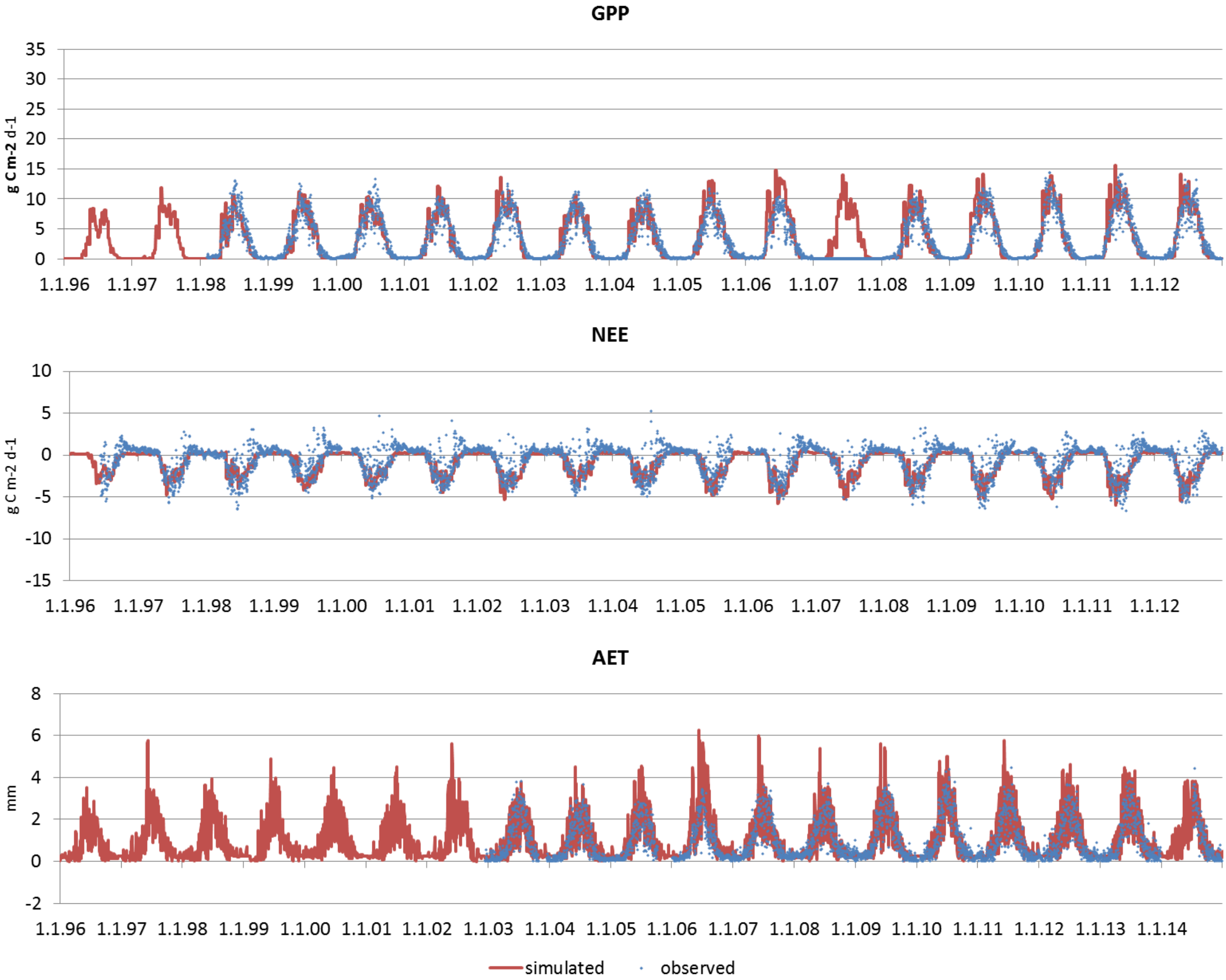

Figure S9 Time series of GPP, NEE, and AET for Hyytiälä; 1996-2014

S3.2.2 Graphical analysis monthly data Hyytiälä

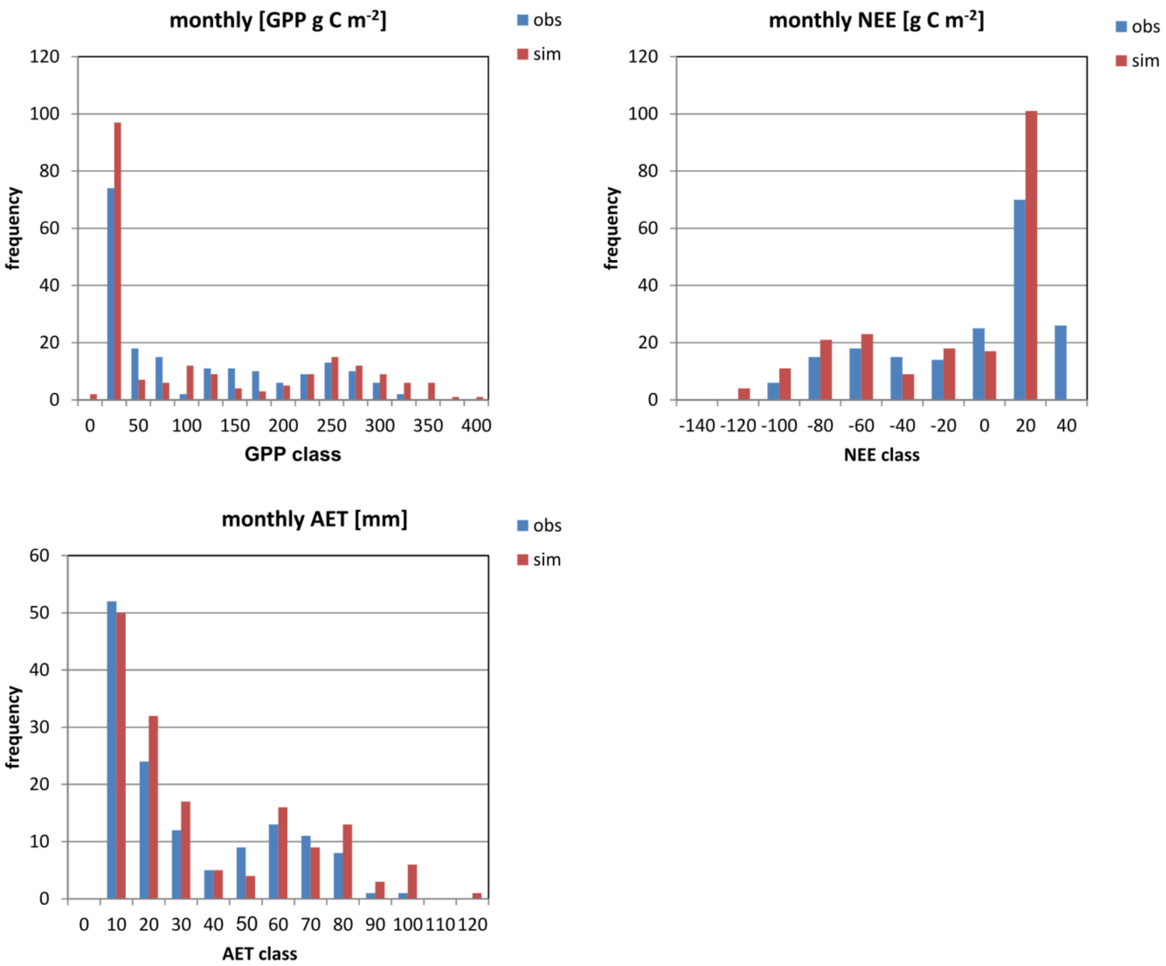

Figure S10 Frequency plots of monthly GPP, NEE, and AET for Hyytiälä; 1996-2014

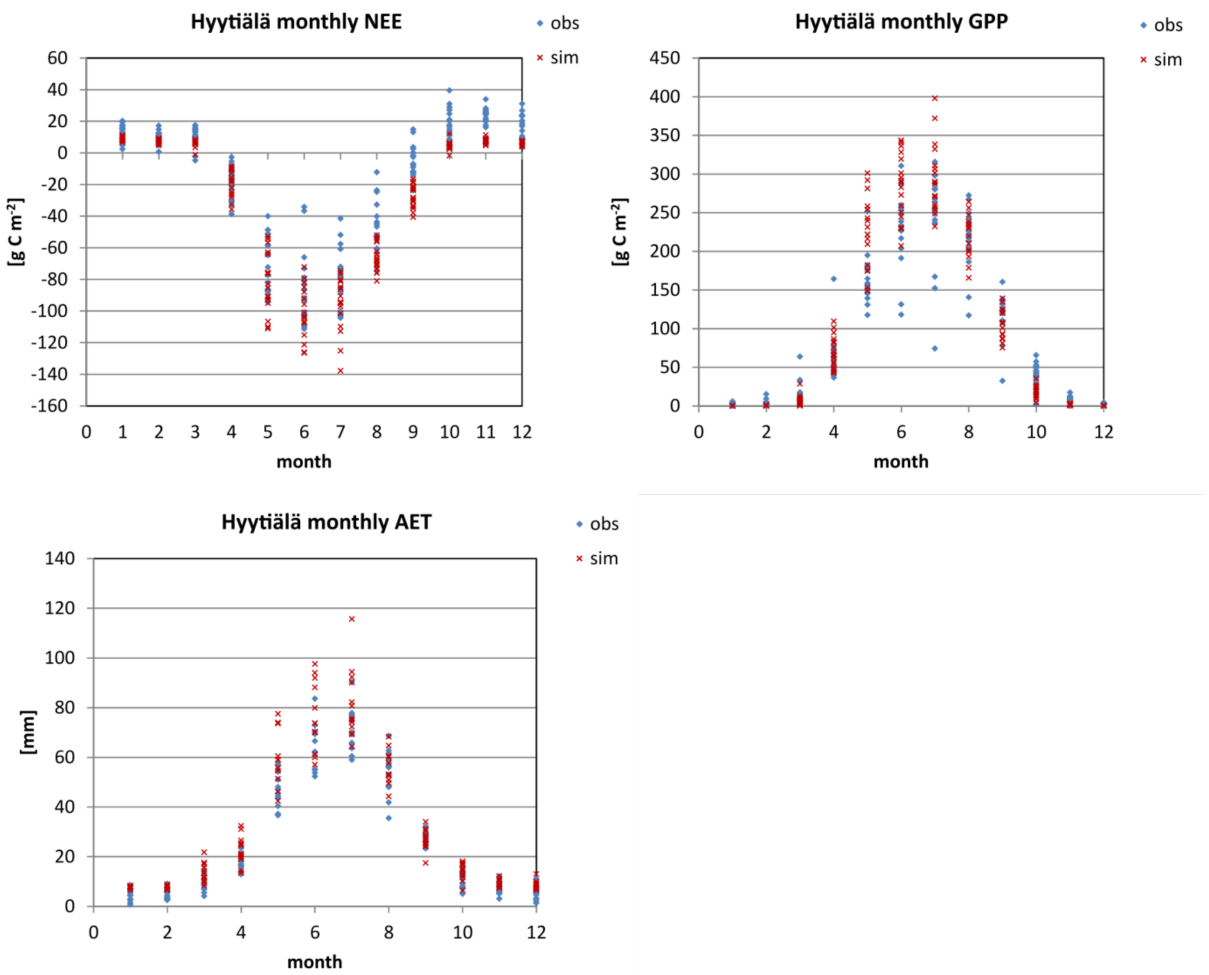

Figure S11 Seasonal cycle of monthly GPP, NEE and AET values obs - observed, sim - simulated in Hyytiälä

S3.2.3 Graphical analysis of soil temperature and water content Hyytiälä

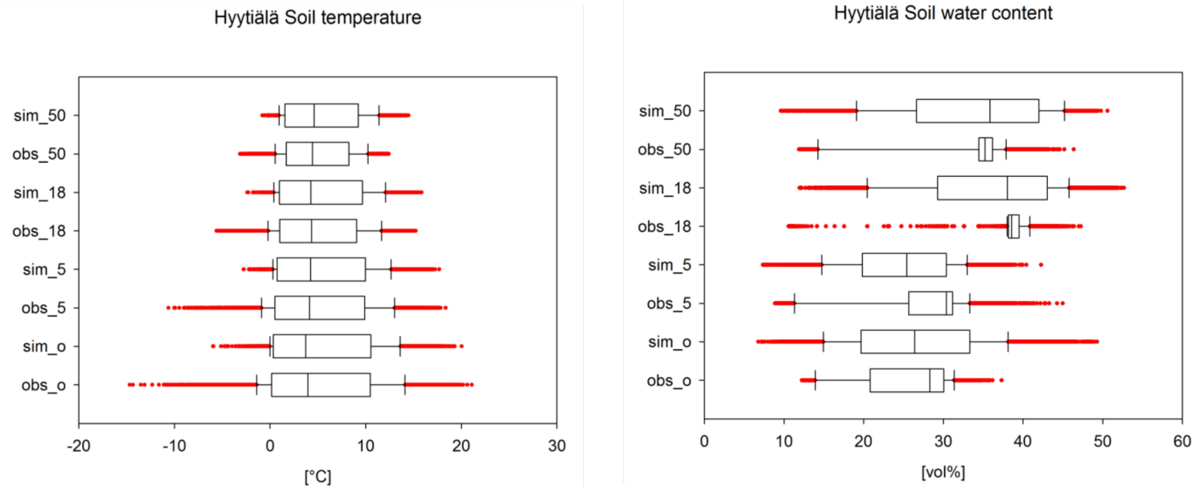

Figure S4. Distribution of magnitude of daily soil temperature and soil water content observed and simulated in different soil layers organic layer, layer in 5, 18, and 50 depth in Hyytiälä. The graph shows the median, the 25th and 75th percentiles box, the 10th and 90th percentiles whiskers and the outliers (red dots).

S3.3 Analysis of deviations of actual evapotranspiration

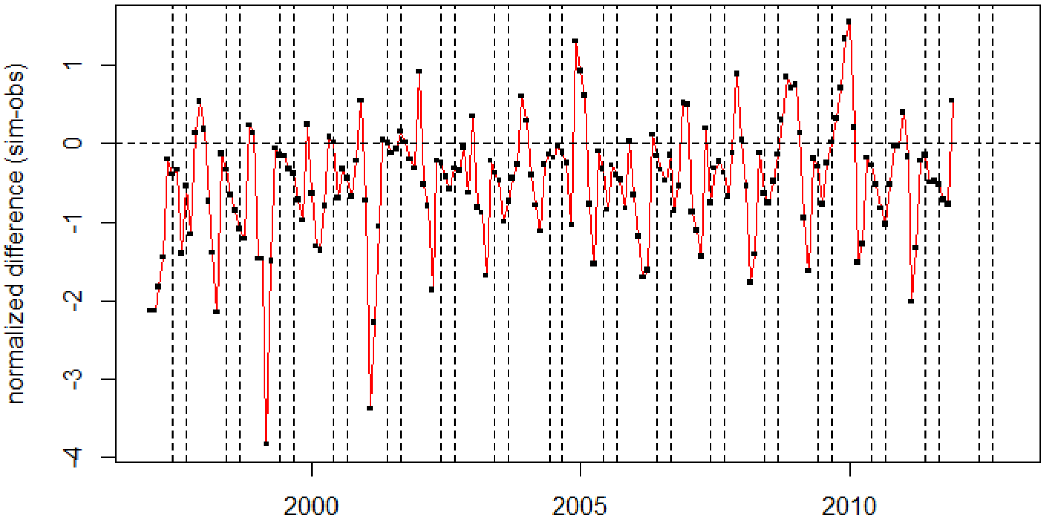

Figure S13. Normalized difference between simulated and observed monthly AET values for the Sorø site. Normalization was done by dividing the mean monthly difference by the mean monthly simulated value. The vertical dashed lines frame the period between June and September.

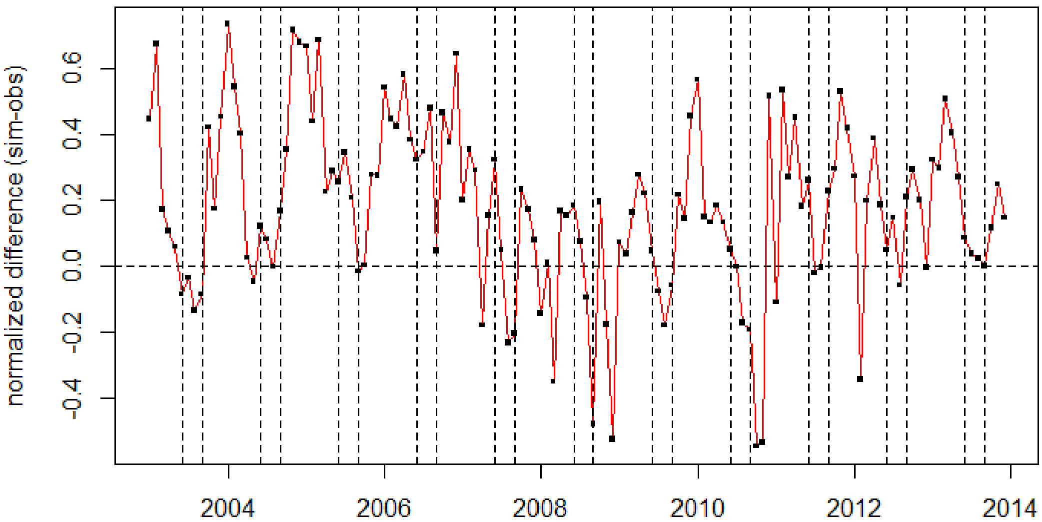

Figure S14. Normalized difference between simulated and observed monthly AET values for the Hyytiälä site. Normalization was done by dividing the mean monthly difference by the mean monthly simulated value. The vertical dashed lines frame the period between June and September.

S4 SOIL TEMPERATURE AND WATER CONTENT HYYTIÄLÄ

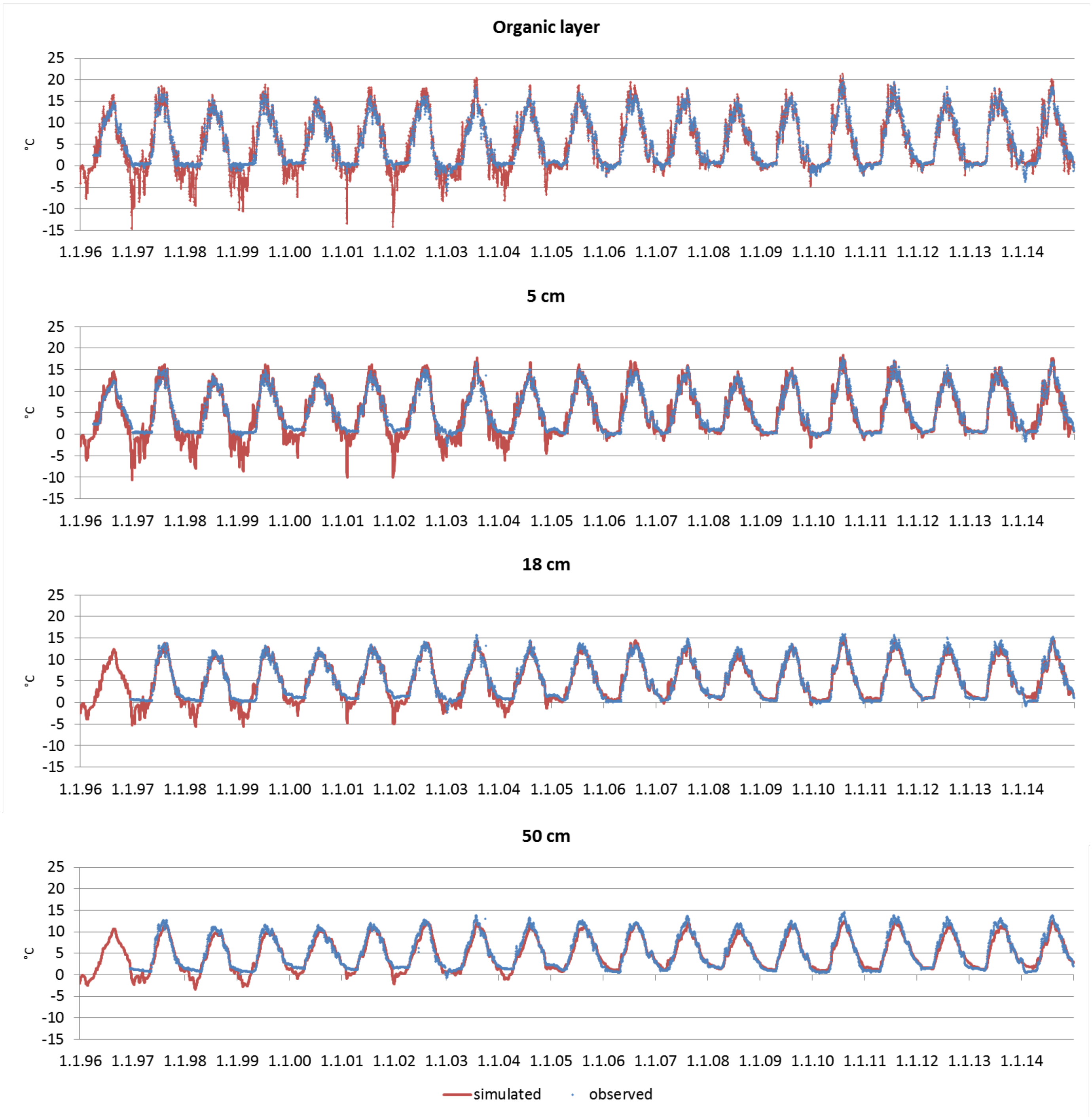

Figure S15. Time series of observed and simulated daily soil temperature for the organic layer and at 5, 18, and 50 cm depth in Hyytiälä for the period 1996-2014.

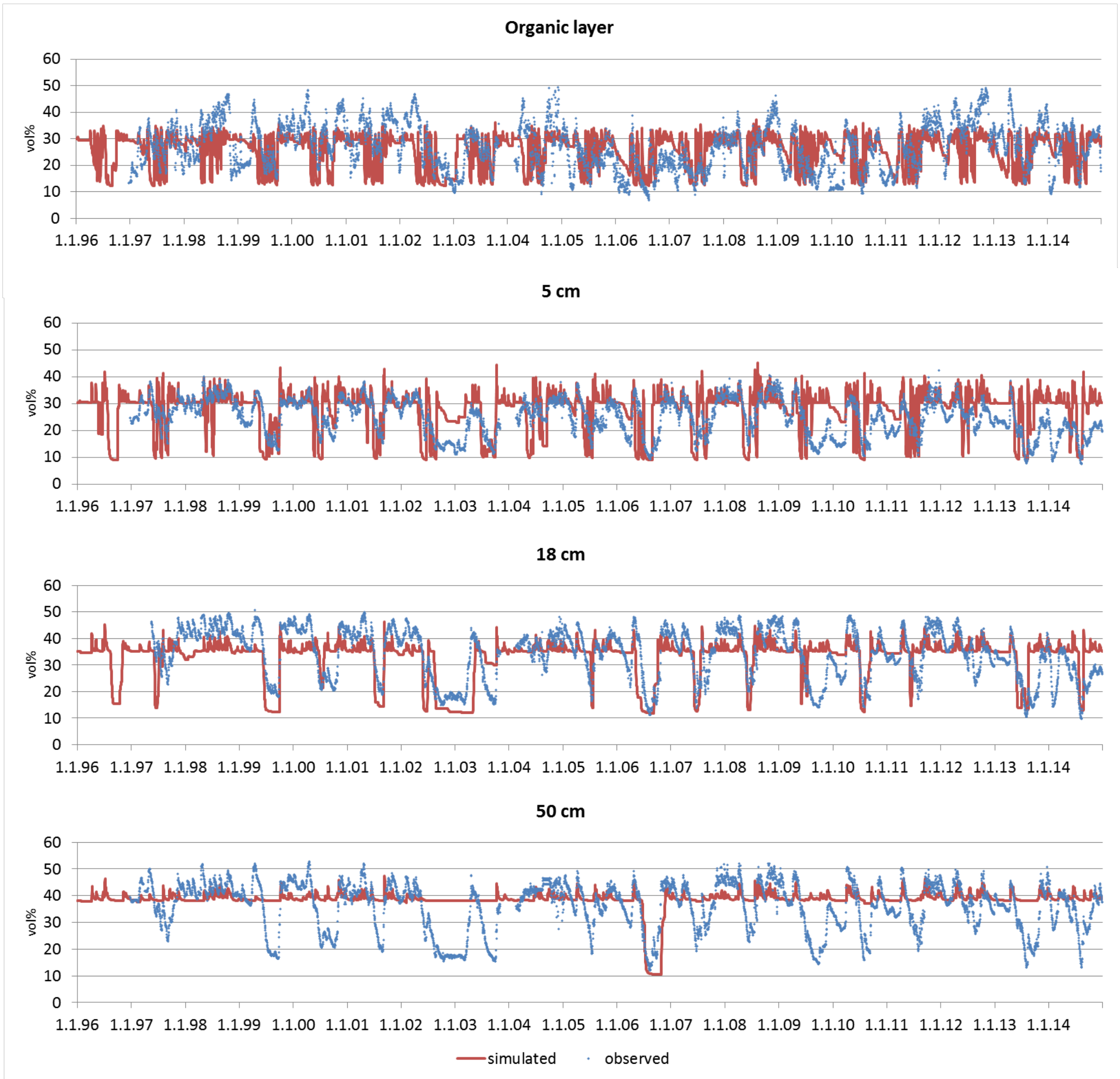

Figure S16. Time series of observed and simulated daily soil water content for the organic layer and at 5, 18, and 50 cm depth in Hyytiälä for the period 1996 2014.

S5 ADDITIONAL DATA

Table S2 Characteristics of the soil profiles of Peitz, Solling, Hyytiälä, and Sorø

	Soil layers Upper depth [cm]	Lower depth	Clay [mass%]	Silt	Sand	Stone content	Pore volume [vol%]	Field capacity	Wilting point	Bulk density [g cm^{-3}]	pH	C/N	C-content [mass%]
Peitz	6.0	0.0	0.00	0.00	0.00	0.00	81.52	30.00	12.00	0.26	2.89	22.60	42.25
	0.0	5.0	7.00	6.00	87.00	0.00	44.00	26.00	7.50	1.12	2.88	33.57	2.60
	5.0	10.0	7.00	6.00	87.00	0.00	44.00	26.00	7.50	1.39	3.33	46.39	0.90
	10.0	20.0	7.00	2.00	91.00	0.00	44.00	26.00	7.50	1.30	3.72	41.95	0.78
	20.0	30.0	7.00	2.00	91.00	0.00	44.00	26.00	7.50	1.40	4.10	44.45	0.45
	30.0	40.0	7.00	2.00	91.00	0.00	44.00	26.00	7.50	1.37	4.16	58.47	0.18
	40.0	60.0	7.00	2.00	91.00	0.00	44.00	26.00	7.50	1.60	4.20	23.33	0.07
	60.0	130.0	0.70	1.30	98.00	0.00	52.00	25.00	9.00	1.60	4.20	25.00	0.05
	130.0	200.0	3.00	1.00	96.00	0.00	52.00	25.00	9.00	1.60	4.20	0.00	0.00
Solling	5.8	0.0	0.00	0.00	0.00	0.00	89.80	34.00	7.00	0.14	2.88	25.52	49.69
	0.0	5.0	19.67	71.07	9.27	0.83	60.99	47.94	13.74	0.82	2.83	18.57	5.29
	5.0	10.0	19.67	71.07	9.27	5.00	60.99	47.94	13.74	1.02	3.21	17.39	2.94
	10.0	20.0	19.67	71.07	9.27	4.67	60.99	47.94	13.74	1.05	3.69	16.18	2.06
	20.0	40.0	19.50	71.20	9.30	3.83	59.20	48.93	13.72	1.11	4.11	13.01	1.22
	40.0	80.0	23.80	61.13	15.07	20.00	40.61	35.58	18.88	1.37	3.99	6.69	0.31

	Soil layers Upper depth [cm]	Lower depth	Clay [mass%]	Silt	Sand	Stone content	Pore volume [vol%]	Field capacity	Wilting point	Bulk density [g cm^{-3}]	pH	C/N	C-content [mass%]
	80.0	100.0	31.80	46.60	21.60	23.00	37.32	36.40	24.48	1.56	3.84	2.73	0.10
	100.0	150.0	31.80	46.60	21.60	96.00	35.50	30.60	26.50	2.10	4.50	0.00	0.00
Hyytiälä	6.0	0.0	0.00	0.00	0.00	0.00	85.71	70.00	12.00	0.20	3.25	28.60	36.95
	0.0	5.5	6.34	14.18	79.48	26.17	48.93	30.38	8.52	0.74	3.41	33.49	3.89
	5.5	22.5	5.72	12.90	81.38	28.65	50.77	28.33	11.61	0.73	4.30	26.28	2.71
	22.5	56.0	6.77	15.02	78.21	29.64	37.84	29.07	10.06	1.27	4.35	46.50	0.37
	56.0	89.0	7.88	10.89	81.23	43.50	28.26	22.21	12.09	1.45	4.54	27.60	0.14
	89.0	10.0	7.88	10.89	81.23	43.50	28.00	22.00	10.00	1.50	4.60	0.00	0.00
Sorø	6.0	0.0	0.00	0.00	0.00	0.00	92.86	26.40	13.10	0.10	4.66	15.86	12.70
	0.0	11.0	10.10	31.00	58.90	0.00	42.00	18.90	8.70	1.29	3.33	14.62	3.23
	11.0	33.0	12.70	27.40	59.90	0.00	42.00	15.40	6.40	1.61	3.92	14.51	0.74
	33.0	50.0	24.40	18.30	57.30	0.00	43.00	24.20	14.80	1.45	5.13	9.44	0.68
	50.0	77.0	13.90	15.10	71.00	0.00	42.00	19.00	9.10	1.46	7.04	25.37	1.04
	77.0	100.0	13.90	15.10	71.00	0.00	42.00	19.00	9.10	1.88	1.32	25.00	1.21
	100.0	150.0	13.90	15.10	71.00	0.00	42.00	19.00	9.10	1.88	1.32	0.00	0.00

Table S3 Available time series of observed data, partially with gaps

Observed data	Peitz	Solling	Hyytiälä	Sorø
Annual data				
Medium height of dominant trees HO	1966-2010	-	-	-
Mean height of all trees MH	-	1967-2010	1995-2011	
Diameter at breast height DBH		1967-2010	1995-2011	-
Geometric mean diameter DG	1966-2010	-	-	-
Stem biomass STBIOM	-	1967-2010	1995-2011	-
Stem volume STVOL	1966-2010	-	-	-
Number of trees	1966-2010	1967-2010	1995-2011	-
Net ecosystem production NEP	-	-	1995-2014	1997-2012
Gross primary productivity GPP	-	-	1995-2014	1997-2012
Actual evapotranspiration AET	-	-	1995-2013	1997-2012
Daily data				
Net ecosystem exchange NEE	-		1996-2014	1996-2012
Total ecosystem respiration TER	-		1998-2014	1996-2012
Gross primary productivity GPP	-		1998-2014	1996-2012
Actual evapotranspiration AET	-		2003-2014	1996-2012
Soil temperature organic layer	-		1996-2014	-
Soil temperature 2 cm	-		-	1996-2012
Soil temperature 5 cm 0 – 10 cm	-		1996-2014	1996-2012
Soil temperature 18 cm 10 – 25 cm	-		1997-2014	-
Soil temperature 50 cm 40 – 60 cm	-		1997-2014	-
Water content	-		1997-2014	-

Observed data	**Peitz**	**Solling**	**Hyytiälä**	**Sorø**
organic layer				
Water content 5 cm 0 – 10 cm	-		1997-2014	-
Water content 8 cm 0-16 cm	-		-	1996-2012
Water content 18 cm 10 – 25 cm	-		1997-2014	-
Water content 50 cm 40 – 60 cm	-		1997-2014	-

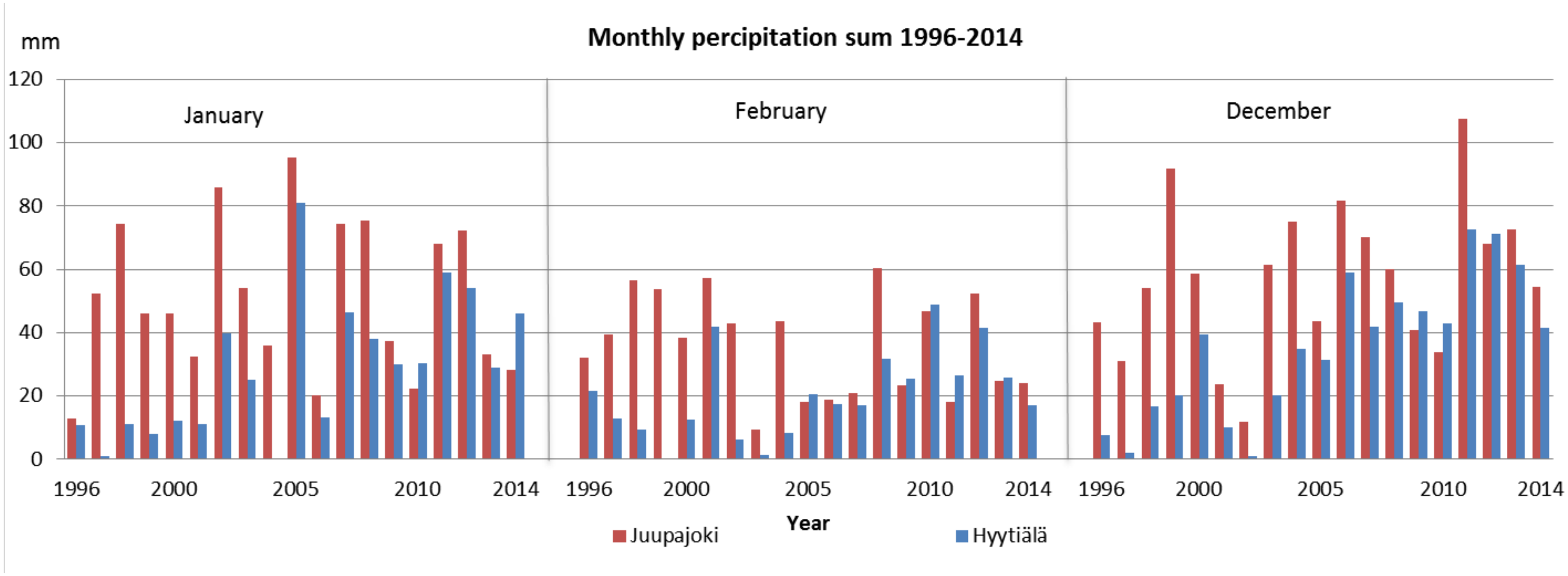

Figure S17 Monthly precipitation sum of the winter month 1996-2014. Comparison of the data from the observation station Hyytiälä and the nearby weather station of the Finnish Meteorological Institute Juupajoki https://en.ilmatieteenlaitos.fi/download-observations#!/, download 23.02.2018. The distance between the two stations is about 300 m.

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