FURTHER DEVELOPMENT AND IMPLEMENTATION OF AN EU-LEVEL FOREST MONITORING SYSTEM
- FUTMON –

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forest monitoring for the future

Modelling the Carbon Budget of Forests at Intensive Monitoring Plots under Current and Future Climate with Biome-BGC

- Final Report -

Hubert Jochheim[1], Michael Janott[1], Oliver Granke[2], Konstantin Olschofsky[3], Richard Fischer[3], Stefan Fleck[4], Reinhard Kallweit[5], Christoph Schulz[6]

[1] Leibniz Centre for Agricultural Landscape Research (ZALF), Institute of Landscape Systems Analysis, Eberswalder Str. 84, 15374 Müncheberg, Germany

[2] Kantstr. 11, 24116 Kiel, Germany; formerly: Johann Heinrich von Thünen-Institut (vTI), Institute for World Forestry, Leuschnerstr. 91, 21031 Hamburg, Germany

[3] Johann Heinrich von Thünen-Institut (vTI), Institute for World Forestry, Leuschnerstr. 91, 21031 Hamburg, Germany

[4] Nordwestdeutsche Forstliche Versuchsanstalt (NW-FVA), Grätzelstrasse 2, 37079 Göttingen, Germany

[5] Landeskompetenzzentrum Forst Eberswalde (LFE), Alfred Möller-Str. 1, D-16225 Eberswalde, Germany

[6] Bayerische Landesanstalt für Wald und Forstwirtschaft (LWF), Hans-Carl von Carlowitz-Platz 1, 85354 Freising, Germany

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ABSTRACT

We present the results of a simulation study on the carbon budget of 28 selected FutMon / ICP Forests level II plots using the model Biome-BGC (version ZALF). For model initialization and calibration mainly data of the FutMon / ICP Forests level II database were used. It contains data on meteorology, soil temperature, stand precipitation, soil moisture, soil properties, forest growth, litterfall, leaf area index, phenology, and other surveys. Additional data on soil respiration were provided by a number of German forest research institutes. The selected plots are located in Austria (1), Belgium (1), Greece (2), Germany (16), Italy (7), Slovakia (2) and cover the tree species Pinus sylvestris (9), Picea abies (9), Fagus sylvatica (7), Quercus cerris (1), Quercus franietto (1), and Quercus robur/petraea (1) in age classes between 60 and 160 years. The simulation periods cover 11 to 34 years. The effects of climate change on the carbon budget of these forest stands were simulated using climate scenarios (A1B and B1) of the FutMon_CLM dataset for the time periods 2040-2059 and 2080-2099 compared to 1990-2009 as reference scenario.

The calibration procedure resulted in a good correlation between simulated and measured values for the plotwise means of all measured variables except for soil respiration.

In 2009, the carbon pools of the investigated forest ecosystems amounted to an average of 323 t C ha^{-1} with main fractions in soil (152 t C ha^{-1} = 47 %) and stem, branch and twigs wood (125 t C ha^{-1} = 39 %), followed by litter (leaf + root) and coarse woody debris (22 t C ha^{-1} = 6.9 %), coarse roots (18 t C ha^{-1} = 5.4 %), needle/leaves (3.9 t C ha^{-1} = 1.2 %), and fine roots (1.8 t C ha^{-1} = 0.6 %). The gross primary production (GPP) was calculated to an average of 14.3 t C ha^{-1} a^{-1} during 1996 – 2009. A fraction of 5.6 t C ha^{-1} a^{-1} (=39 % of GPP) leaves the ecosystem by maintenance respiration, 2.0 t C ha^{-1} a^{-1} (= 14 %) by growth respiration, and 4.0 t C ha^{-1} a^{-1} (=28 %) by heterotrophic respiration. The net primary production (NPP) amounts to 6.7, the net ecosystem production (NEP) to 2.7 and the net biome production (NBP) to 1.8 t C ha^{-1} a^{-1}. The carbon pool change rates average to +1.5 t C ha^{-1} a^{-1} for vegetation, +0.40 t C ha^{-1} a^{-1} for the litter + coarse woody debris pools, and to -0.07 t C ha^{-1} a^{-1} for the soil.

Under the A1B scenario the simulated changes of carbon balance between 1990-2009 and 2080-2099 amount on average to +4.8 t C ha^{-1} a^{-1} for GPP (+35 %), to +2.9 t for maintenance respiration (+55 %), to +0.43 t for growth respiration (+22 %), to +0.78 t for heterotrophic respiration (+20 %), to +0.65 t for NEP (+26%), and to +0.58 t C ha^{-1} a^{-1} for NBP (+35%) compared to the reference period (1990-2009). The increase of carbon stocks accelerates by +0.66 t C ha^{-1} a^{-1} (47 %) in vegetation. The increase of litter (+0.04 t C ha^{-1} a^{-1} = +17%) compensates for the decrease of coarse woody debris (-0.04 t C ha^{-1} a^{-1} = -28%). The simulated decrease of soil carbon during the reference period was accelerated by -0.09 t C ha^{-1} a^{-1} (+64%). The vegetation period was elongated by 2 to 19 days. For the B1 emission scenario and the medium time period (2040-2059) the simulated effects are mostly smaller.

The results on soil temperature, water budget and the aboveground carbon budget can be assessed as reliable, whereas the results on the belowground carbon budget are relatively uncertain, due to different reasons that are discussed.

The FutMon / ICP Forests level II database is very useful for the application of complex models like Biome-BGC. Measurement of belowground carbon pools and fluxes as well as transpiration rate would significantly improve the reliability of the simulation results. However, these surveys were neither foreseen in the FutMon project, nor are they part of the ICP Forests monitoring programme. The measurement of complete sets of parameters that are optional in the ICP Forests monitoring programme would enable the application of the model on a significantly higher number of plots.

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Abbreviations

bd = bulk density of soil

CWD = coarse woody debris

fc = field capacity

GPP = gross primary production

GR = growth respiration

HR = heterotrophic respiration

kf = saturated hydraulic conductivity

LAI = leaf area index

LF_L = leaf litterfall

LF_{SF} = stem + fruit litterfall

LF_R = root litterfall

MR = maintenance respiration

NBP = net biome production

NEP = net ecosystem production

NPP = net primary production

pv = pore volume

pwp = permanent wilting point

RR = root respiration

SG = stem growth

SLA = specific leaf area

SOC = soil organic carbon

WE = wood export by harvest

ΔL_{L+FR} = change rates of litter carbon pool (leaf + fine root)

ΔCWD = change rates of coarse woody debris carbon pool (stem + coarse root)

ΔSOC = change rates of soil carbon pool

ΔVeg = change rates of vegetation carbon pool

1 Introduction

Carbon budget of forest ecosystems

Just over the half of the anthropogenically induced greenhouse effect is related to carbon dioxide emissions (Schulze 2006). Because of strong interactions between physical and biochemical processes, more and more coupled climate-carbon cycle models are used to assess effects of the anthropogenic emission of greenhouse gases. According to previous calculations, only about half of the emitted carbon dioxide remains in the atmosphere. About one third is absorbed by the oceans and about 20% by the terrestrial biosphere. Globally, about 500 Gt C are stored in terrestrial vegetation. Compared to the quantities stored in oceans and in fossil pools, this represents a minor amount, which however reacts very sensitively and quickly to climate changes and human intervention.

Within the carbon cycle in the terrestrial biosphere, forests play a significant role. During photosynthesis plants remove carbon dioxide from the atmosphere and transform it into biomass. A part of the assimilated carbon is respired for energy production (autotrophic respiration) and emitted into the atmosphere as CO_2. The rest is converted into plant biomass (leaves, trunks, branches, twigs, fruits and roots).

Vegetation litter enters the soil where it is respired by animals and microorganisms for energy production (heterotrophic respiration). Due to differences between biomass production and respiration, a pool of soil organic matter approximately three times the size of the plant biomass carbon pools built up over centuries and continues to increase (Schulze 2006).

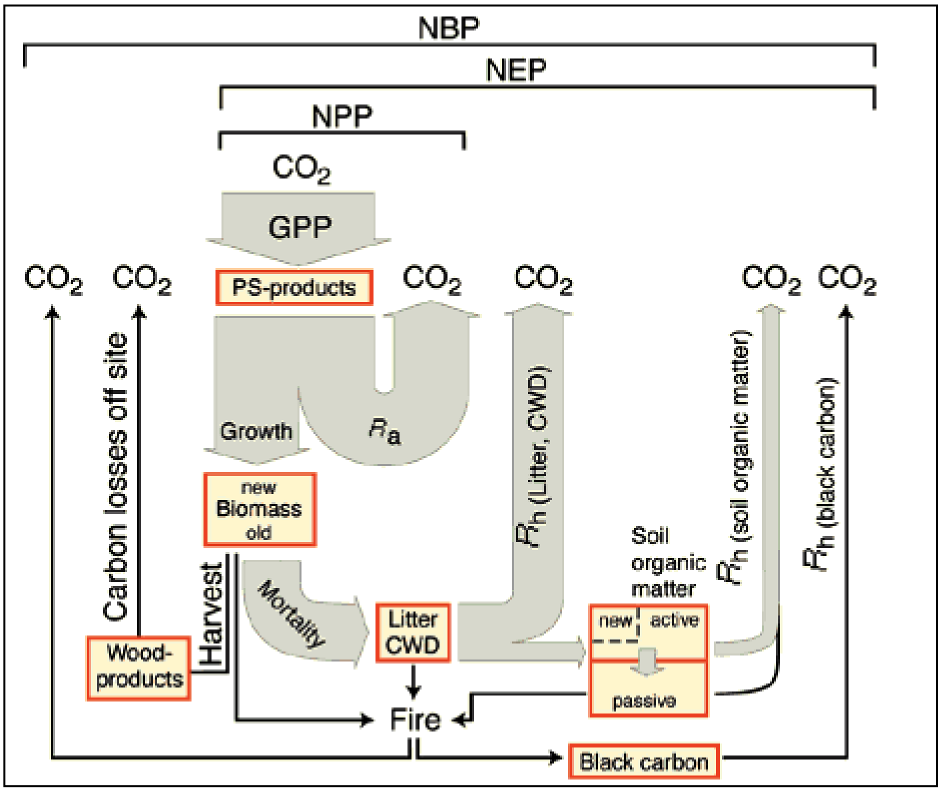


Fig. 1 Carbon balance of terrestrial ecosystems (after Schulze 2006)

The turnover of carbon in terrestrial ecosystems is not a closed cycle, but is in open exchange with the atmosphere. Carbon balances are not only regulated by the assimilation and respiration processes, but fire and harvest activities must also be considered. The definition of carbon balance (Schulze, 2006) distinguishes between gross primary productivity (GPP), which includes the photosynthetic CO_2 fixation, net primary productivity (NPP), i.e. the difference between assimilation and plant respiration (maintenance respiration (MR) + growth respiration (GR)), which is the net growth of all plant organs, and the net ecosystem productivity (NEP), which in addition to the NPP accounts for heterotrophic respiration. The net biome productivity (NBP) also takes into account fire and harvest related carbon losses of the ecosystem. The relationships are shown schematically in Fig. 1.

Balancing of carbon stocks in forests is essential because the majority (15 of 23) of the countries of the European Union have chosen the option to credit carbon sinks in forestry according to article 3.4 of the Kyoto Protocol (UNFCCC 2006). In the first commitment period (2008 to 2012), all changes in the carbon storage of above- and belowground biomass, litter layer, dead wood and soil organic carbon have to be credited (UNFCCC 2006). Only if it is transparently shown for a carbon stock that it is not a source, it does not have to be accounted (UNFCCC 2006).

For quantitative detection of carbon stocks and their changes, however, considerable methodological and data related challenges need to be taken into account. The large spatial variability of the C concentrations in soils as well as the small amplitude of annual changes compared to the stocks cause considerable uncertainties. Therefore, stock changes in ecosystems can at reasonable effort only be exactly estimated if monitored for long periods (decades).

Simulation models can be applied to assess the carbon balance of forest ecosystems if they are sufficiently parameterized, calibrated and validated with measured data. By modelling, the impact of changed environmental conditions on forest ecosystems can be calculated and therefore they can provide information on the future behaviour of ecosystem carbon stocks.

Lacking better data, previous greenhouse gas inventories assume that the stocks in litter and soil do not change over time (Strogies et al. 2003), (Nabuurs et al. 2003b). In Germany, results of a second soil survey, covering data on soil carbon stocks, are currently evaluated (Bolte et al. 2011). Large-scale models point out, that it is likely that the carbon stocks of the litter layer and the soil are even still growing (Liski et al. 2002).

Global climate change and consequences to forests

Due to global changes, rising concentrations of climatologically relevant atmospheric trace gases concentrations are expected. Global climate models predict an increase of temperature in the range of 1.8 to 4.0 °C within 100 years (IPCC 2007). In Europe, the drought risk is going to increase from west to the east. In the Mediterranean regions, additionally the risk of fire events is going to increase (Lindner et al. 2010).

In Central Europe, the number of hot days per year is going to increase to a number that is presently occurring in Southern Europe (Christensen et al. 2002, Beniston et al. 2007). In winter, heavy precipitation events are predicted to increase in Central and Northern Europe, while during summer time they are expected to increase in the northeast of Europe and to decrease in Southern Europe.

The possible impacts of climate change to forests include a number of opportunities and threats (Zebisch et al. 2005, Boisvenue and Running 2006). The rising atmospheric CO_2 concentrations may have a fertilizing effect (Jarvis 1999, Körner 2006). The water use efficiency might improve because the stomata may be opened to a lower extent in order to fulfil the carbon demand (Field et al. 1995). Higher temperatures may increase yield by optimizing photosynthesis, by accelerating litter decomposition, and by elongating the vegetation period (Schaber 2002, Badeck et al. 2004, Rötzer et al. 2004, Menzel et al. 2006, Hyvönen et al. 2007). On the other hand, heat waves and drought periods may lower the growth of forests (Breda et al. 2006, Rennenberg et al. 2006). Forest fires and wind throw as well as forest pests, stimulated by climate change may destroy forests over large areas (Suckow et al. 2005, Zebisch et al. 2005, Schlick and Möller 2007).

Until now, only few simulation studies on carbon budget analyses under climate change aspects have been carried out based on data of level II plots. In the SILVISTRAT project different models have been compared (Kellomäki and Leinonen 2005, Lindner et al. 2005). Model applications were conducted for some level II plots in a number of German federal states (Gerstengarbe et al. 2003, Rötzer et al. 2005, Stock 2005). During a C2 activity of the ForestFocus project additional measurements of soil respiration at a number of German level II plots were conducted in order to improve the reliability of two applied simulation models (Badeck et al. 2007, Meiwes et al. 2007, Jochheim et al. 2009a). Tree growth analyses of a large number of level II plots were analysed based on 5-years inventories and related to nitrogen and acid deposition (de Vries et al. 2007, Laubhann et al. 2009, Solberg et al. 2009).

Objectives

Global change has the potential to modify the relation between biomass assimilating and dissimilating sub-processes and to change the resulting carbon sequestration. The politically relevant questions in this context are to understand the sub-processes of the carbon budget of forest ecosystems, to assess the source-sink relationship for carbon under current and future climate conditions, and to find measures for carbon mitigation by forest management.

Within the ICP Forests level II program, the aboveground parts of the carbon balance were assessed by measurements at European forest sites. Modelling can be used to link different kinds of measured data, in order to calculate the complete carbon budget of the investigated plots and to give estimates for future development of the carbon budget by applying climate scenarios. This requires a huge amount of information, of which most parts started to be measured at “core plots” of the FutMon project. Based on the level II database and additionally available data sources it should be evaluated whether the measurements carried out at level II plots are suitable to investigate the carbon budget of the forests.

In the present study, a modified version of the Biome-BGC model is used to calculate the carbon budget of selected level II plots and to simulate the impact of future climate conditions on the carbon budget.

The present study focuses on the following questions:

- Are the level II plots suitable to investigate the carbon budget of forests?
- How much carbon is stored and turned over in forests of level II plots?
- Do the investigated forests act as carbon sources or as sinks?
- How does the carbon source-sink relationship develop under expected future climate conditions?

2 Methods

2.1 Investigated sites

In this investigation Biome-BGC was applied to 28 FutMon / ICP Forests level II plots (Tab. 1). The simulated plots were selected as result of a data availability analysis. They cover Austria (1), Belgium (1), Greece (1), Germany (16), Italy (7), and Slovakia (2). Within these countries, their altitude ranges from planar to alpine. Long term averages of the climate conditions are presented in Tab. 1 and Fig. 2. The annual mean air temperature ranges from 4 to 12 °C, mean precipitation from 580 to 1680 mm a^{-1} and mean nitrogen deposition from 3 to 44 kg N ha^{-1} a^{-1}. More information on the climatic conditions is presented in Tab. A1 in the appendix. The dominant tree species on the plots are *Pinus sylvestris* L. (9), *Picea abies* [L.] Karst. (9), *Fagus sylvatica* L. (7), *Quercus cerris* L. (1), *Quercus frainetto* Ten. (1), and *Quercus robur* L. */ petraea* [Matt.] Liebl. (1). The full tree species names are abbreviated by the terms pine, spruce, beech and oak in this text. The trees mainly belong to older stand age classes (for 2010) between 60 and 160 years.

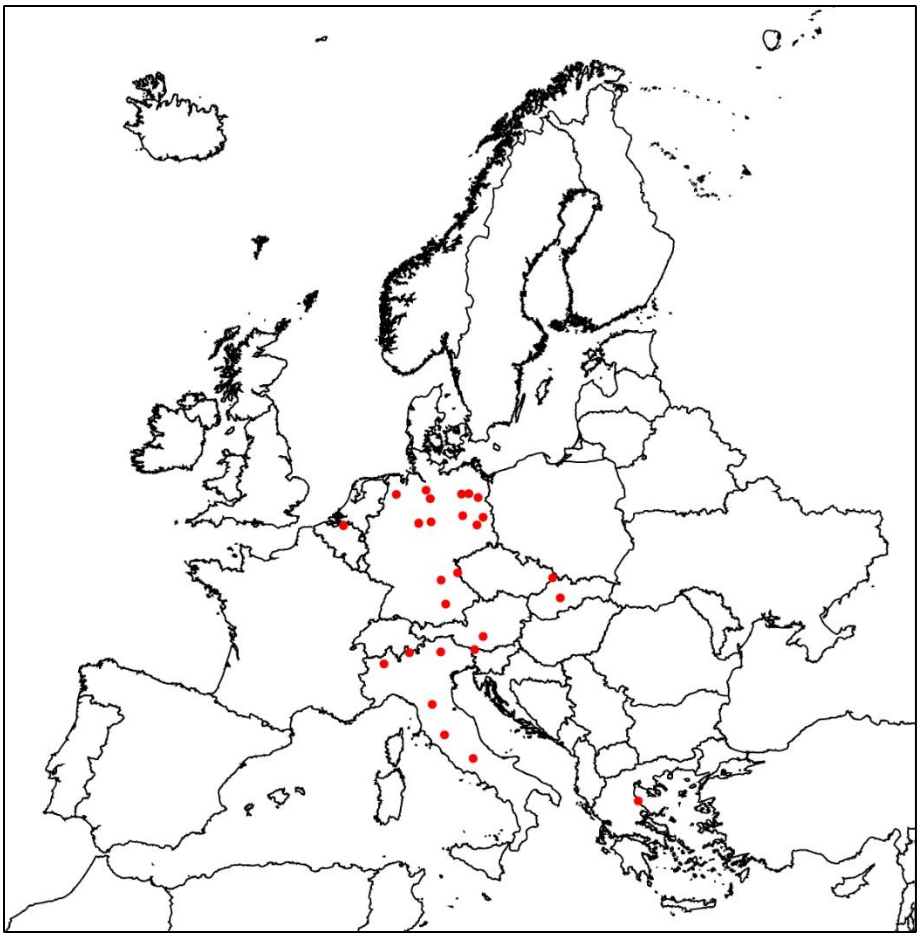


Fig. 2 Investigated plots

Tab. 1 Description of main site conditions of the investigated plots

plot no	main tree species	tree age in 2010 (a)	altitude (m a.s.l.)	longi-tude (Dec°)	latitude (Dec°)	air tempe rature (°C)	precipi-tation (mm a^{-1})	avg. N depos. (kg N ha^{-1} a^{-1})
AT0016	Picea abies	125	1526	14.10	47.05	4.3	1107	3.2
BE0015	Pinus sylvestris	72	15	4.52	51.30	10.7	681	34.9
DE0301	Fagus sylvatica	129	115	10.28	52.84	9.4	817	18.1
DE0302	Picea abies	63	600	10.42	51.86	7.1	1388	23.7
DE0303	Picea abies	62	660	10.42	51.86	7.0	1388	31.7
DE0304	Fagus sylvatica	163	504	9.58	51.76	7.1	1134	33.2
DE0305	Picea abies	128	508	9.58	51.77	7.1	1134	43.7
DE0307	Pinus sylvestris	66	30	7.86	52.91	9.2	830	35.5
DE0308	Q. robur/petraea	128	109	9.91	53.18	8.5	826	23.1
DE0901	Pinus sylvestris	108	406	11.32	49.41	7.7	832	17.1
DE0908	Picea abies	92	840	12.4	49.76	6.0	911	21.5
DE0919	Fagus sylvatica	158	508	11.66	48.41	8.1	790	21.0
DE1201	Pinus sylvestris	83	63	12.43	53.1	8.5	619	10.7
DE1202	Pinus sylvestris	78	71	12.97	53.14	8.4	663	10.3
DE1203	Pinus sylvestris	106	66	13.64	52.98	8.6	608	7.3
DE1204	Pinus sylvestris	98	110	12.56	52.19	9.1	602	10.8
DE1205	Pinus sylvestris	86	60	13.57	51.80	8.4	623	9.8
DE1206	Pinus sylvestris	89	60	14.02	52.16	9.0	583	9.8
GR0002	Quercus frainetto	84	725	22.78	39.78	12.0	1090	10.8
IT0001	Fagus sylvatica	142	1525	13.58	41.85	6.3	1070	7.2
IT0006	Fagus sylvatica	63	975	11.12	44.10	10.0	1355	11.0
IT0008	Picea abies	123	825	13.58	46.48	7.2	1678	9.4
IT0009	Quercus cerris	63	675	11.90	42.83	12.4	881	7.2
IT0010	Picea abies	103	1175	93.50	46.23	7.6	1419	9.7
IT0012	Fagus sylvatica	83	1125	80.67	45.68	7.2	1288	17.5
IT0017	Picea abies	143	1775	11.48	46.35	4.7	1059	4.9
SK0206	Fagus sylvatica	83	575	19.03	48.63	7.7	679	10.0
SK0209	Picea abies	98	875	18.57	49.50	6.9	1192	17.3

2.2 Data for model application

The main **sources of input data** used for model application are listed below (Tab. 2):

- FutMon / ICP Forests level II data base (processing status: 08.06.2011), supplied by the vTI - Institute of World Forestry, Hamburg (http://www.futmon.org)

- Some additional data of German level II plots received from three German Forest Institutes (Bavaria: Bayerische Landesanstalt für Wald und Forstwirtschaft (LWF), Brandenburg: Landeskompetenzzentrum Forst Eberswalde (LFE), Lower Saxony: Nordwestdeutsche Forstliche Versuchsanstalt (NW-FVA). Parts of these data were measured during a ForestFocus project at selected plots and described in (Badeck et al. 2007, Meiwes et al. 2007).
- Evaluated data on forest growth of level II plots, supplied by the ICP Forests Expert Panel on Forest Growth
- Soil profile data from the BioSoil project (Hiederer et al. 2011), supplied by the Forest Soil Co-ordinating Centre at INBO
- Historical meteorological data from NCEP/NCAR reanalysis dataset (2.5° regular grid, (Kalnay et al. 1996)) provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, http://www.esrl.noaa.gov/psd/, and gridded (0.25° regular grid) and station data of the E-OBS dataset (http://eca.knmi.nl/download/ensembles/download.php (Haylock et al. 2008), http://eca.knmi.nl/dailydata/predefinedseries.php (Klok and Tank 2009))
- FutMon_CLM dataset as data for future climate projections provided by the vTI Institute of World Forestry, Hamburg
- European soil database (ESDB) (Tóth et al. 2008), (http://eusoils.jrc.ec.europa.eu/ESDB Archive/ESDBv2/index.htm)

The structure of the FutMon / ICP Forests level II database is determined by the specifications for data submission (http://www.futmon.org/submission.htm). The database consists of 65 forms covering the topics meteorology, deposition, air quality, crown condition, ozone injury, phenology, leaf area index (LAI), litterfall, tree vitality, growth and increment, ground vegetation, soil water analysis, needle and leaf analysis for trees and ground vegetation. 35 of these forms are used for the application of Biome-BGC. The assignment of these 35 database forms to the data needed for Biome-BGC is shown in Fig. 3.

For use with Biome-BGC, the data from the database have to be processed (Fig. 3). We developed SPSS routines (SPSS for Windows, Rel. 19.0.0. 2010, Chicago SPSS Inc.) to extract the required data from the FutMon / ICP Forests database, and store them into an appropriate format for model initialization and calibration/validation.

Biome-BGC interacts with a large number of data sets. The data can be grouped into **boundary conditions** with data on meteorology, atmospheric CO_2, and N deposition, and into manmade boundary conditions in form of forest management rules, **initial values** for carbon and nitrogen pools in plant, litter and soil compartments, initial values for soil water and snow, and the root depth, the **model parameters** with soil parameters and physiological model parameters, and **calibration or validation data** with time series of stand internal meteorology, soil temperature, soil moisture and carbon pools and fluxes like forest growth and litterfall. This chapter presents the data used and explains how the data were derived from the available sources.

The data fluxes diagram for Biome-BGC including the derivation of model input and calibration data from the level II database is shown in Fig. 3. Grey boxes indicate thematic fields of data from the level II database with the names of the forms in blue letters and from other sources. Arrows in dark blue show SPSS routines that in the upper part of the figure process the data to produce the model input data (boxes in light blue) and in the lower part compare the calibration data with the simulation outputs (green boxes). Relations between model specific input files are marked as red arrows. Black arrows show the input and output fluxes of the model during a simulation run. The initialization and restart files do not contain measured data but are important for the model settings.

The input data needed for initialisation, parameterisation, calibration, and validation of Biome-BGC can be classified according to their necessity for model application. Based on our experience we classified the variables into three groups:

1. absolutely necessary for model application (meteorology, N deposition, initial values of stem and soil organic carbon pools, physical and hydrological soil parameters),
2. highly needed for model calibration (forest growth, litterfall, soil respiration, initial root depth and distribution, stand precipitation, canopy transpiration, soil moisture, phenology),
3. useful for model calibration (initial value of litter and coarse woody debris C pool, LAI, time series of SOC, C:N ratios, SLA, soil temperature, tree ring analysis).

The necessity classification in combination with results of a data availability and quality analysis is needed to decide, for which plots Biome-BGC can be basically applied and how reliable the simulation results will be.

Some of these measurable input variables can be derived from literature or from pre-simulation results and have therefore not to be measured, unconditionally. Some of these replacement processes are more appropriate than others and some variables cannot be replaced. It also has to be considered how sensitive the model reacts on changes of the replaced values. The calibration data do not have to be available in order to run the model but are essential to determine not measurable site and vegetation specific model parameters (e.g. allocation parameters and turnover fractions) during the calibration process.

Tab. 2 Data needed for model application

	Level II database (form name)	**German forest institutes (NW-FVA, LFE, LWF)**	**other sources**
meteorology	MEM	x	NCEP/NCAR, E-OBS
climate projections			FutMon_CLM
stand precipitation	MEM, DEM	x	
soil moisture	MEM, SWA	x	
soil temperature	MEM	x	
stem volume / forest growth	INV	x	ICP Forests Expert Panel on Forest Growth
harvest	INV	x	yield tables
litterfall	LFM	x	
LAI	LAM	x	
phenology	PHE	x	
specific leaf area	LFM	x	
C:N in foliage	FOM	x	
C:N in litterfall	LFM	x	
N deposition	DEM	x	
atmospheric CO_2			Mauna loa / SRES
soil parameter	PFH, SOM, SWA	x	Biosoil, ESDB
rooting depth	PRF	x	
soil C time series		x	
soil respiration		x	

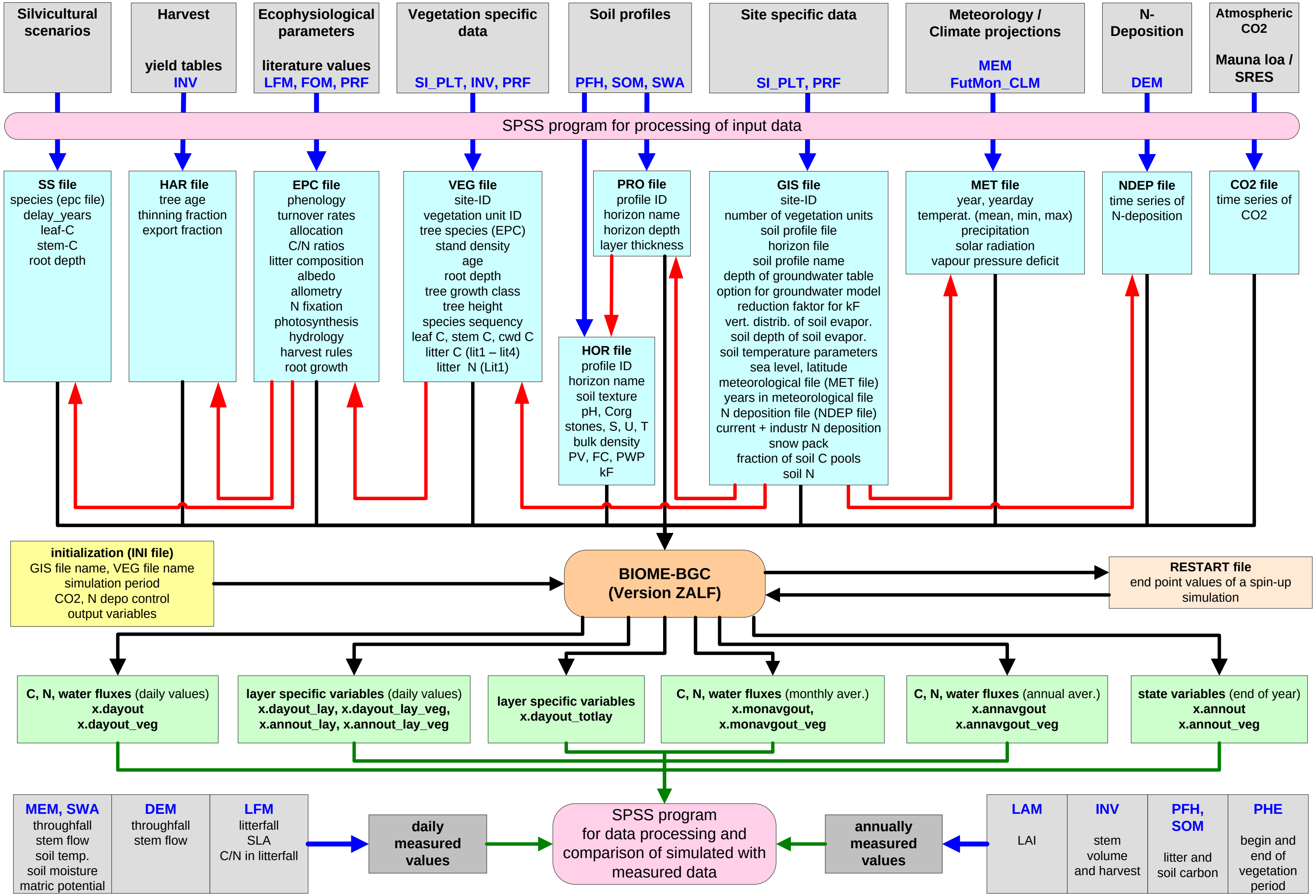


Fig. 3 Data flux diagram of Biome-BGC (version ZALF) for level II database applications (further explanation see text)

2.2.1 Driving Forces

2.2.1.1 Meteorological data

The meteorological data needed by Biome-BGC cover information on the daily maximum, minimum and mean air temperature, the daily precipitation sum, the daylight average vapour pressure deficit, and the daylight average shortwave radiant flux density.

The measurements of meteorological data on level II plots mainly started between 1994 and 1996. The latest data of the level II data base used here were measured in 2009/2010. For some plots longer time series from former projects exist. The level II data base contains measured meteorological parameters from the open field at sites close to the forest area, from tower measurements above the canopy, or from nearby weather stations.
Since the time series of the meteorological data contain many gaps, external data sources are needed for carrying out gap filling. For the German level II plots we used gap filled meteorological data provided by the German forest institutes. The gap filling procedure for other European plots uses the E-OBS dataset (version 5.0, 0.25° regular grid, (Haylock et al. 2008) for daily air temperature (minimum, maximum, average) and precipitation. Global radiation was derived from sunshine duration or cloud cover fraction of the closest meteorological station of the E-OBS dataset (Klok and Tank 2009). Relative humidity was derived from the NCEP/NCAR reanalysis dataset (Kalnay et al. 1996) that contains daily meteorological data in a 2.5° grid. In order to shift the E-OBS and NCEP/NCAR data to the level of measured meteorological data, monthly means of external data and measured data on the plot were correlated for the overlapping periods and the linear regression parameters were used to correct the daily external data used for gap filling.

The vapour pressure deficit (VPD) used by Biome-BGC is calculated from daily minimum and maximum values of relative humidity, if available, or from dew point after (Allen et al. 1998) taking the minimum air temperature as dew point temperature. This is possible if the annual ratio of potential evapotranspiration / precipitation is <2.5 (Thornton et al. 2000). In other cases VPD is calculated from daily averages of relative humidity. Daylength is computed as a function of date and latitude.

2.2.1.2 Climate projections

Climate projection data of the FutMon_CLM dataset (vTI Institute of World Forestry, Hamburg) was derived from the CLM dataset (Hollweg et al. 2008) at the basis of the IPCC-SRES emission scenarios A1B and B1 and the global climate model ECHAM5-MPIOM of the Max Planck Institute for Meteorology, Hamburg (Jungclaus et al. 2006). The FutMon_CLM dataset was calibrated for level II plots by measured values on plots and the CRU dataset. The dataset consists of a calibration run (C20) for the period 1961-2000 and scenarios A1B and B1 for 2001-2100.

The data of the reference periods (1990-2009) of the climate scenarios (see chapter 2.4) are compared to the measured values (see details in Fig. 4, Tab. A1). As an average, the climate scenarios show similar values for temperature, precipitation, and relative humidity, even though larger differences for single plots occur. The global radiation is on average 13 % lower than the measured data. Very large differences exist for the temporal distribution of precipitation. While in the measured data precipitation occurs on 59 % of all days, this value decreased to 44 % in the scenarios. One exception with the opposite result exists for plot AT0016.

The climate conditions of the future, compared to the reference scenarios are shown in Fig. 5. In the simulation period 2040-2059 the temperature increases by 1.1 °C and 1.6 °C for B1 and A1B, respectively, compared to the reference period, whereas the shift for the periods 2080-2099 is larger (2.4 °C, 3.6 °C for B1 and A1B, respectively). In the climate projections a shift of precipitation from summer to winter time is predicted. Increasing winter precipitation overcompensates the reductions in summer resulting in increasing annual precipitation sums (76 – 107 mm a^{-1} = 8 - 11 %, depending on period and scenario).

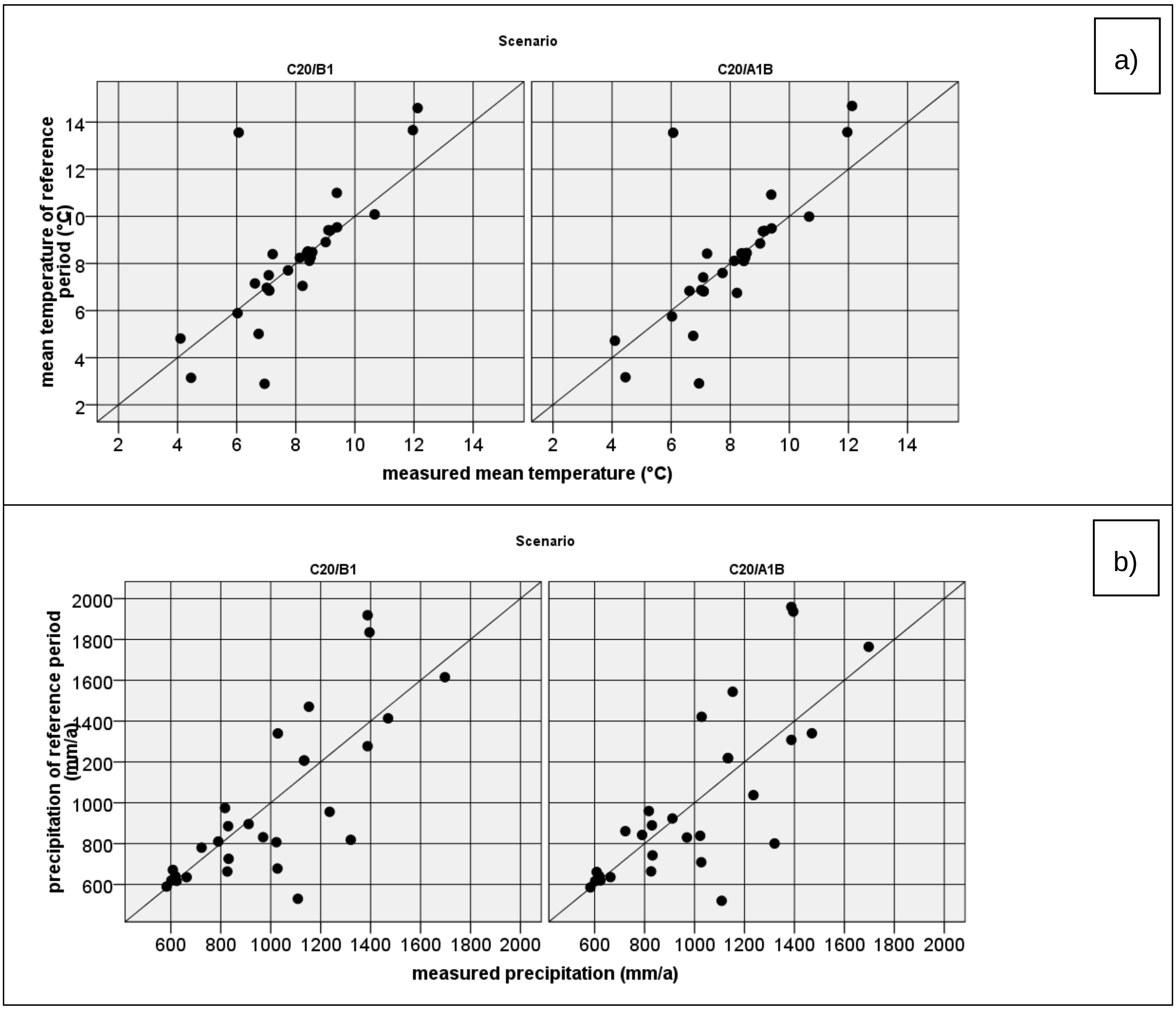


Fig. 4 Plotwise means of measured values versus values from the FutMon_CLM dataset (scenarios C20/A1B and C20/B1) for the calibration period, a) mean air temperature; b) precipitation; c) number of precipitation days (%); d) relative humidity; e) global radiation

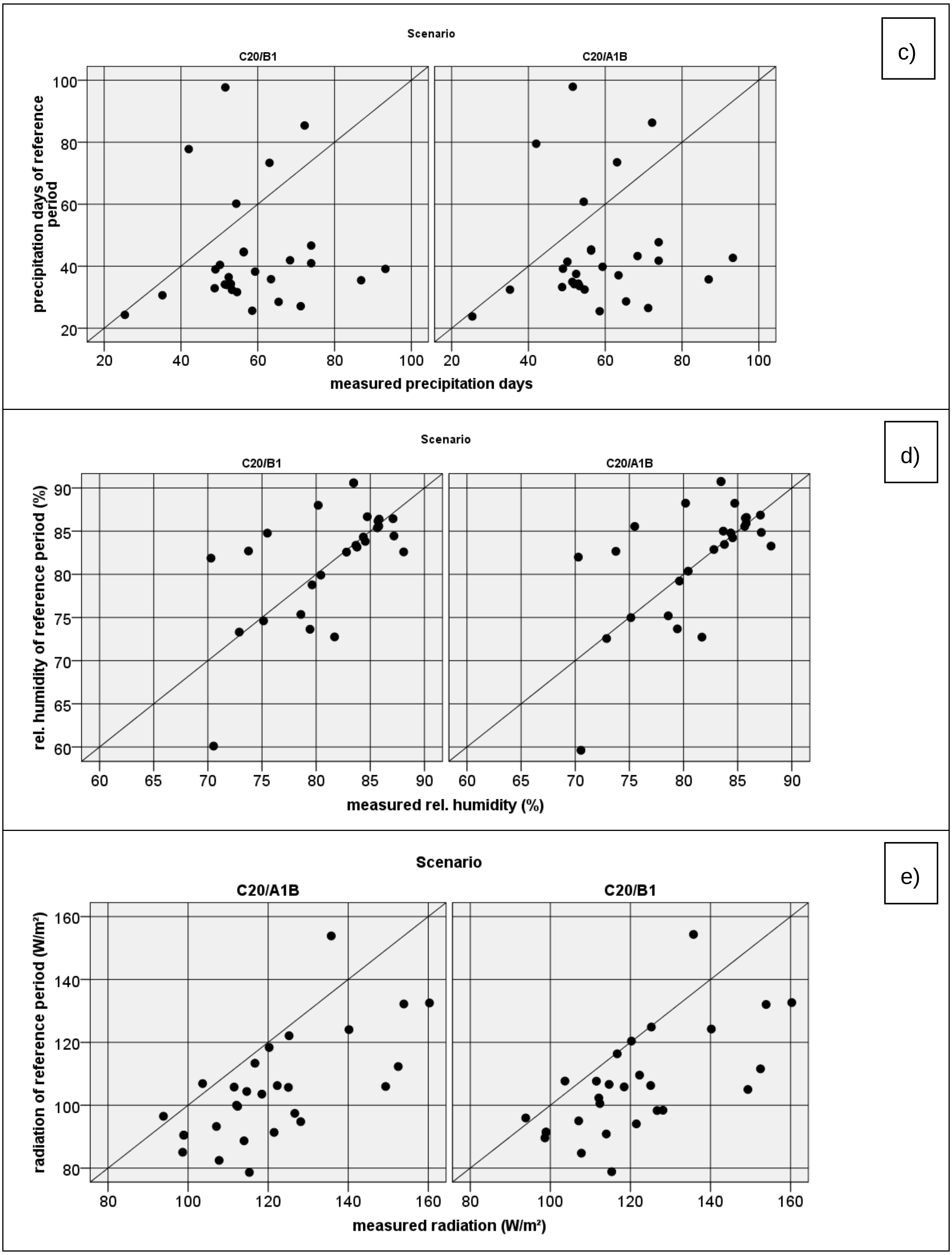


Fig. 4 (continued) Plotwise means of measured values versus values from the FutMon_CLM dataset (scenarios C20/A1B and C20/B1) for the calibration period, a) mean air temperature; b) precipitation; c) number of precipitation days (%); d) relative humidity; e) global radiation

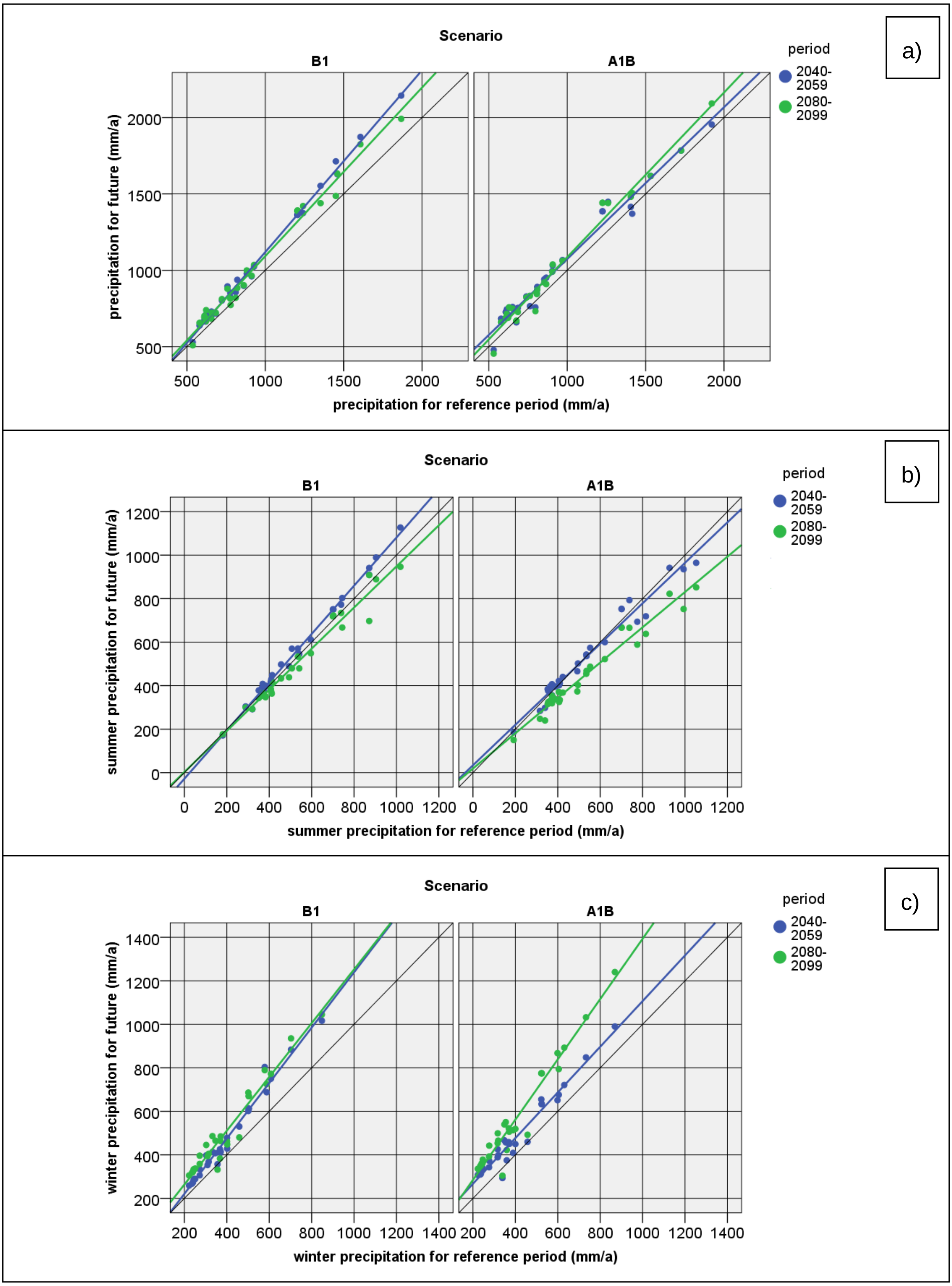


Fig. 5 Annual averages/sums of a) precipitation, b) summer precipitation (May-Oct), c) winter precipitation (Nov-Apr), d) temperature, e) rel. humidity, and f) short wave radiation during the simulation periods of used future climate projections (scenarios B1 and A1B) compared to those of the reference period (1990-2009)

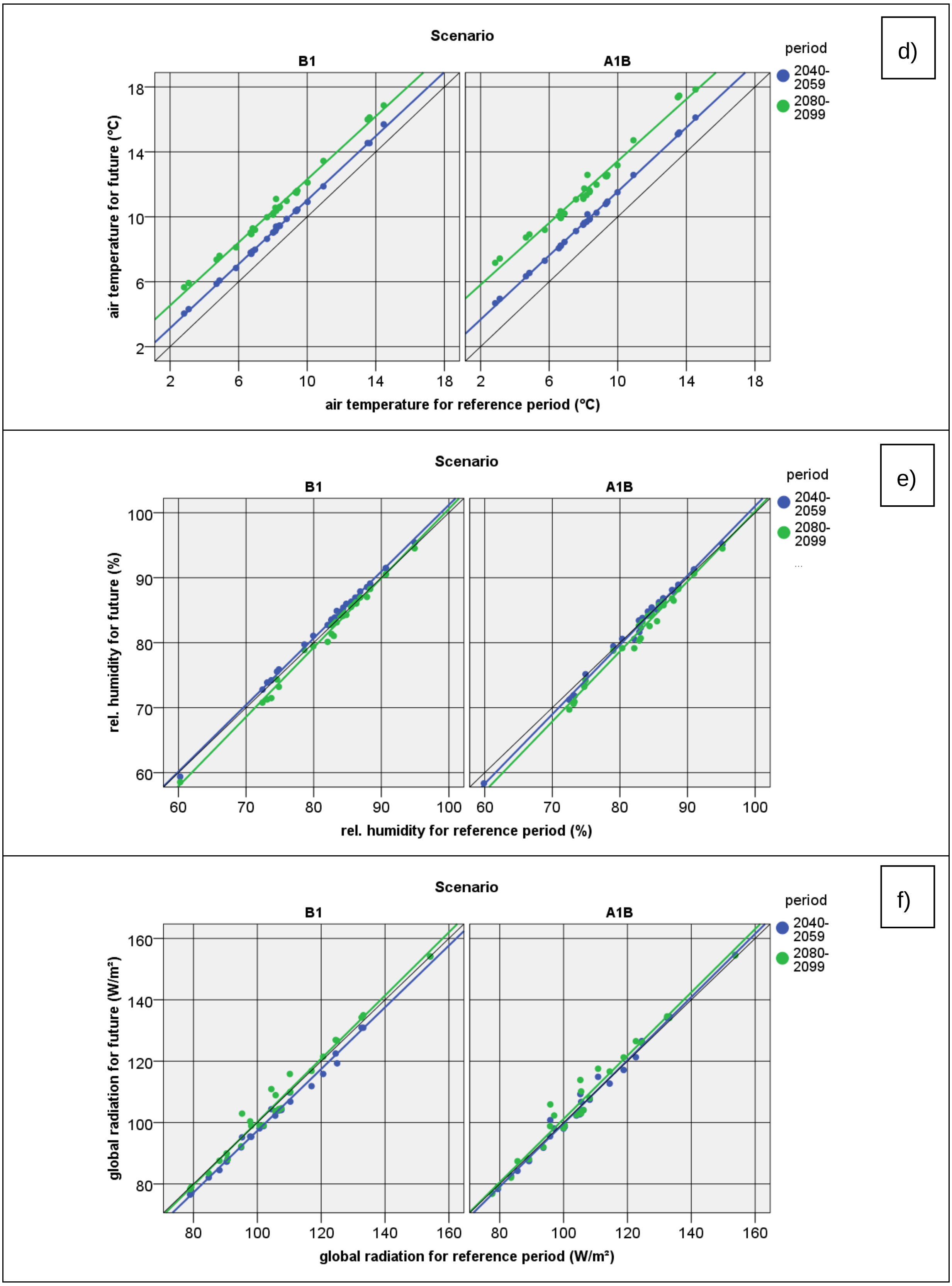


Fig. 5 (continued) Annual averages/sums of a) precipitation, b) summer precipitation (May-Oct), c) winter precipitation (Nov-Apr), d) temperature, e) rel. humidity, and f) short wave radiation during the simulation periods of used future climate projections (scenarios B1 and A1B) compared to those of the reference period (1990-2009)

2.2.1.3 CO_2 concentrations

The simulation runs are carried out taking into account changing atmospheric CO_2 concentrations. For historical periods the data of the station Mauna Loa were used (ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2_annmean_mlo.txt), whereas for climate change scenarios the data of the IPCC-SRES scenarios B1 and A1B, calculated with the global carbon budget model BERN were used (http://www.ipccdata.org/ancilliary/tar-bern.txt). In these scenarios the CO_2 concentrations are rising from 382 ppm in 2006 up to 540 and 703 ppm in 2100, respectively.

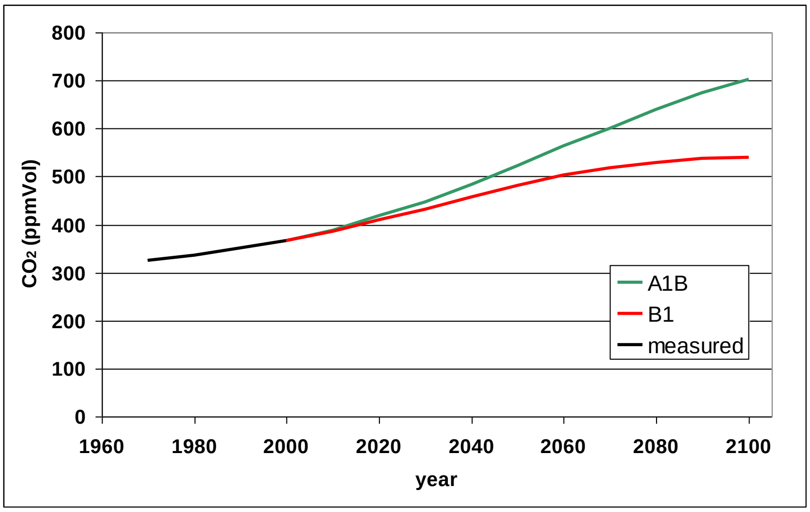


Fig. 6 Atmospheric CO_2 concentrations of the past and the IPCC-SREC emission scenarios A1B and B1

2.2.1.4 Nitrogen deposition

The simulation model considers the total nitrogen deposition of the level II plots as annual sums. The total deposition of nitrogen was calculated as the sum of NH_4^+-N and NO_3^--N in throughfall and stemflow using the DEM form of the level II database.

For the German sites, NO_3^- total deposition rates were calculated with an approach of (Ulrich 1994) and the NH_4^+-deposition following an approach of (Draaijers and Erisman 1995), calculated by the German forest institutes and used instead of the database content.

Missing values were interpolated linearly. If negative values were computed for the pre-simulation period, the plotwise mean values were used instead.

2.2.2 Initial values

The model needs initial values for water, carbon, and nitrogen pools that were derived as described below.

2.2.2.1 Carbon and nitrogen pools of forest stands

The model has to be initialized with information on carbon pools of stem and leaf, tree age, root depth and a parameter for vertical root distribution.

The model Biome-BGC does not differentiate between stem wood, branches and twigs. Thus, the total aboveground wood volume has to be considered by calculating it from timber volume and expansion factors (Dieter and Elsasser 2002). For calculation of carbon pools literature values for wood density (Dietz 1975) and carbon concentration (Trendelenburg and Mayer-Wegelin 1955) were used.

The INV form of the level II database contains data on standing wood volume regardless of the tree species. These data were recently recalculated from the single treewise inventory data (IPM form of the level II database) by the ICP Forests Expert Panel on Forest Growth and are not yet part of the level II database. For the German plots additional inventory data were supplied by the German forest institutes.

In case of pre-simulation runs, initial wood carbon pools were derived by linearly extrapolating these values with observed average tree growth rates.

The initial values of coarse and fine roots were derived using observed or species-specific ecophysiological parameters from literature (root depth, parameter for vertical root distribution, allocation parameters).

For all vegetation compartments the nitrogen pools were calculated from carbon pools and C:N ratios, that are ecophysiological model parameters.

2.2.2.2 Litter and soil organic carbon and nitrogen pools

The initial total soil organic carbon of a layer is calculated model internally from horizon specific soil properties, i.e. mass percent of organic carbon, fine soil bulk density, layer thickness, and volumetric stone content. Total organic carbon of a specific layer is then divided into four carbon pools with different turnover rates (fast, medium, slow, recalcitrant) according to the fractions of each pool that have to be specified as model parameter and are included as constant values for all layers during the whole simulation period.

The initial litter carbon pool is calculated from observed mean annual leaf litterfall, annual leaf turnover rate, and the carbon content of foliage. If the mentioned data were missing, the initial litter carbon pool was derived from the steady-state value. The litter pool is split into labile, unshielded cellulose, shielded cellulose, and lignin litter pools and assigned to the first soil layer. The fractions of the four soil C pools as well as the four litter C pools were set to values that minimize changes during model run.

The corresponding litter and soil organic nitrogen pools are calculated by the model from these carbon pools by multiplying it with the corresponding C:N ratios.

2.2.2.3 Coarse woody debris

The coarse woody debris is divided into two fractions: stem and coarse root woody debris. In the context of Biome-BGC the coarse stem woody debris is defined as the sum of standing and lying dead wood including fallen branches and twigs. The initial values can be defined by the user. If there were no data available, we set 4% of the standing volume as a default value. In case of a distinct gradient of coarse woody debris the initial value was adjusted in order to obtain low change rates.

Coarse root woody debris is calculated model internally from stem wood by using the ecophysiological model parameters for allocation, turnover, and vertical root distribution.

2.2.2.4 Soil water and snow

Since the model runs start at the 1st January and the plots are restricted to the northern hemisphere, the soil was assumed to be water saturated at this time. Therefore, the initial soil water content of the layers was set equal to the field capacity.

The amount of snow was set to probable values depending on the geographical position and meteorological data prior to simulation start, if available.

2.2.2.5 Root depth

The initial root depth can be derived for few plots from measured data in the form PRF of the level II database containing information on effective rooting depth. Some forest institutes provided measured data or estimates. If there were no data available, a pre-simulation with a hypothetical forest stand at the age of 1 year and the original site conditions was run until the present forest stand age was reached. The resulting root depth was set as initial root depth.

2.2.3 Model parameters

2.2.3.1 Soil profile

For the definition of the soil profile the horizons have to be split into 2, 5, 10, or 20 cm layers. Chemical and physical soil parameters are soil texture with sand, silt, and clay fractions, organic carbon concentration, pH values, bulk density, soil hydrological parameters as pore volume (PV), field capacity (FC), permanent wilting point (PWP), saturated hydraulic conductivity (kf) of the fine soil, and the volumetric stone and gravel content.

In the FutMon / ICP Forests and BioSoil databases (Hiederer et al. 2011) the soil profile data are available in two forms, the PFH and the SOM. The SOM form contains soil data in an aggregated form for constant steps of soil depths (organic layer, 0-5, 5-10, 10-20, 20-40, 40-80 cm). The description of soil depth is restricted to 80 cm. In contrast, from the PFH form and the German forest institutes horizon-wise data down to the rock were measured in many cases and were used if available. In the PFH form, the stone content is recorded in five classes, only. Here, the class mean was used as input data.

The soil hydraulic parameters PV, FC, PWP, and kf are taken from soil profile data when available and derived from soil texture, C_{org} concentrations, and bulk density according to the German soil classification rules KA5 (AG Boden, 2005) else. During the calibration process the measured parameters of PV, FC, PWP, and kf were fitted to match the measured soil moistures and therefore may differ slightly from the original values.

From the SOM form, the soils were only recorded down to a maximum depth of 80 cm. This is not satisfying for modelling if in fact the soil is deeper. An estimation of the real soil depth and rooting depth was carried out by combination of the plot with the European Soil Database (ESDB) (Tóth et al. 2008) similar to the procedure described by (Wiedemann et al. 2001). For this, the plot information was matched with the ESDB by soil type (according to the BioSoil data), plot coordinates, and land use class.

2.2.3.2 Vertical root distribution

The simulation model needs the root depth and vertical root distribution for the determination of the water uptake and the vertical distribution of carbon allocation to coarse and fine roots. The vertical root distribution can be taken from the PRF-form, but there are only few entries. Else, species-specific values are taken from literature (Jackson et al. 1996).

2.2.3.3 C:N ratios in biomass compartments

C:N ratios of living leaves/needles and after nitrogen retranslocation in litterfall, as well as in fine and coarse roots, and in wood are essential model parameters. These parameters were mostly available for foliage and litterfall and recorded in the FOM and LFM form. The root and wood C:N ratios were available only exceptionally.

In case of missing C:N ratios, observed species-specific means (Fig. 7) or literature values, taking into account the humus form of the site were used.

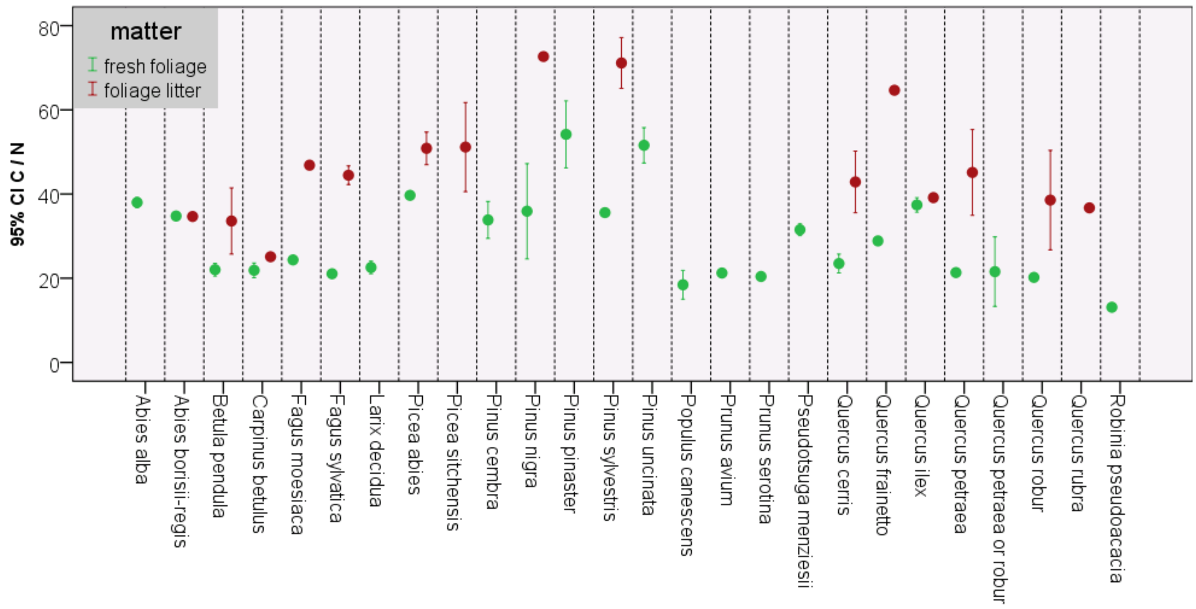


Fig. 7 Means and standard deviation of observed species-specific C:N values in foliage and in leaf litter

2.2.3.4 Specific leaf area

Specific leaf area was computed from the area and mass of foliage samples recorded in the LFM form of the level II database for several plots and years or was partly available from additional measurements. This parameter allows the calculation of leaf area index from measured leaf litterfall and is a valuable model parameter.

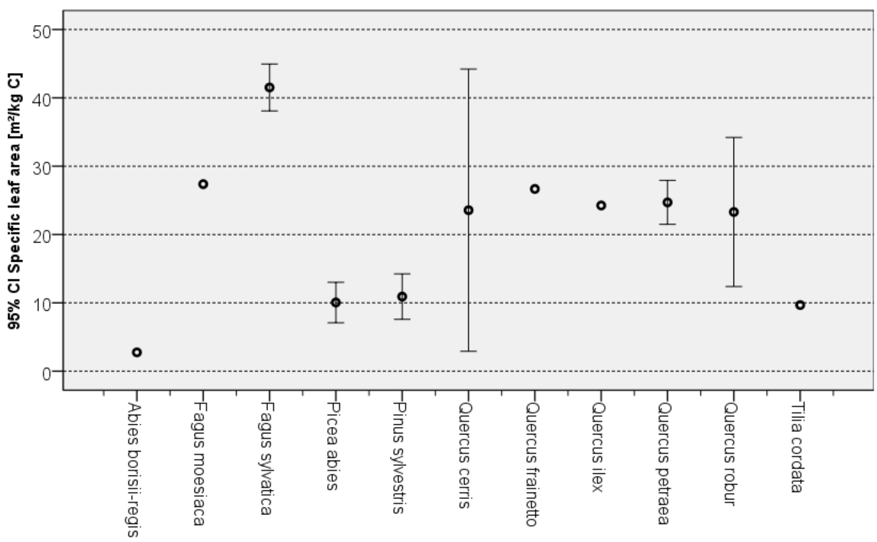


Fig. 8 Means and standard deviation of observed species-specific specific leaf area [m² (kg C)$^{-1}$] values in foliage and in leaf litterfall

2.2.4 Model calibration data

2.2.4.1 Soil temperature

Soil temperature inside the forest is measured at most of the analysed level II plots in several soil depths and could be used for model calibration without any data transformation. It was extracted from the MEM form of the level II database.

2.2.4.2 Stand precipitation and canopy evaporation

Canopy throughfall of water from forest canopies and additionally stemflow in beech forests are measured on a large number of plots. Stand precipitation as a sum of throughfall and stemflow is measured in weekly, bi-weekly or monthly time steps. Additionally to the continuously measured precipitation, which was used as input for simulation models, open field precipitation is measured in identical time steps like stand precipitation. But since interception is calculated as the difference of precipitation and stand precipitation, two series of interception rates (one daily and one weekly/monthly) can be calculated, resulting in possible inconsistencies that have to be considered when interpreting simulated and measured data.

2.2.4.3 Canopy transpiration

Canopy transpiration is neither part of the mandatory nor of the optional level II measurement program. But in few cases there additional data on measured transpiration rates were available and provided valuable data for water budget calibration (plot DE0304, measured in 1996 (Schipka et al. 2005), plot DE0305, measured in 1996 by Jutta Heimann (not published), plot DE1202, measured in 1998/1999 (Lüttschwager 2001, Lüttschwager and Remus 2007).

2.2.4.4 Soil moisture

Measured volumetric soil water contents were available in the MEM form of the level II database for many plots from TDR or FD probes. At some plots also measured matric potentials from tensiometers were available. In this case soil moisture was calculated from matric potential using van Genuchten parameters, which were either measured (form SWA) or derived with the help of pedotransfer functions from soil properties (Schaap et al. 2001, Teepe et al. 2003). The resulting water contents differ depending on the used pedotransfer function.

2.2.4.5 Phenology and leaf area index

Measurements of phenology and LAI were introduced during the FutMon project and are stored in the forms PHE and LAM of the level II database. In case that these data were not available in the level II database, additional data were provided by the German forest institutes.

The length of the vegetation period was determined by the time period between leaf flushing and litterfall. For the estimation of leaf area index (LAI) different methods were used, resulting in large differences between the obtained values. For comparison with simulation results we used maximum, minimum, and mean values of these LAIs.

2.2.4.6 Tree growth

The tree growth was calculated from changes of remaining wood, taking into account removed wood per plot summarized over all tree species and age classes. These data were derived from the INV form of the level II database or from the recalculated inventory data supplied by the ICP Forests Expert Panel on Forest Growth as described in chapter 2.2.2.1.

For reasons of quality control the derived stem growth rates were compared with estimated yield classes as given in SI_PLT form of the level II database.

2.2.4.7 Litterfall

Data on litterfall provide valuable data for calibration of carbon budget models, as these fractions are substantial sinks for photosynthesis products and allocation patterns may be altered under changing environmental conditions.

The measurement of litterfall was started for a larger number of plots during the FutMon project. Fractions recorded in the LFM form of the level II database can be classified into foliar litter, woody litter, and several fractions of reproductive organs.

Biome-BGC divides the aboveground litterfall into foliar and non-foliar fractions. For this reason the measured sub-fractions were aggregated into these two fractions. Litterfall from all tree species was summarized. Production of belowground coarse and fine root litter was considered in the model, additionally, but not measured at level II plots.

2.2.4.8 Soil organic carbon

Soil properties including C_{org} concentrations were analysed in the first survey at the start of the ICP Forests level II program. This survey is restricted to distinct soil layer depths down to 80 cm soil depth. Only elected plots were reanalysed for horizons down to rock depth during the BioSoil project. For more information on soil data see chapter 2.2.3.1. Time series of soil organic carbon pools exist only exceptionally, if the plots were investigated during former research programs and became level II plots later or if additional analyses were conducted. In this investigation time series were only available for the plots Solling beech and Solling spruce (plots DE0304 and DE0305).

2.2.4.9 Soil respiration

Measurements on soil respiration processes provide valuable data for calibrating a key process of the carbon budget. Especially, approaches for differentiation between heterotrophic and root respiration are helpful for the calibration of the allocation processes.

Soil respiration measurements were carried out during a ForestFocus project at selected German level II plots (Badeck et al. 2007, Meiwes et al. 2007, Schulz and Klein 2011). For the present investigation those data were provided by the German forest institutes.

2.3 The simulation model Biome-BGC (version ZALF)

The biogeochemical model Biome-BGC (vers. 4.2, http://www.ntsg.umt.edu/models/bgc/) was developed for simulating the dominant processes of water, carbon and nitrogen dynamics in generalised biomes on a daily time resolution and is applied mainly at regional to global scales. The original model considers natural forests, but not managed ones. For a detailed model description of the original model version the reader is referred to (Running and Coughlan 1988, Running and Gower 1991, Thornton 1998, Thornton et al. 2002). Complete sets of input parameters for major natural temperate biomes are provided by (White et al. 2000) and for tree species growing in Central Europe by (Churkina et al. 2003, Mollicone et al. 2003, Pietsch et al. 2005, Cienciala and Tatarinov 2006, Jochheim et al. 2009b). The sensitivity to model parameters was tested by (White et al. 2000, Tatarinov and Cienciala 2006).

The extended version of the model Biome-BGC (version ZALF) (Jochheim et al. 2007, Puhlmann and Jochheim 2007) allows for the simulation of managed forest stands at plot to regional scales, considering more species and site specificity with regard to climate change. The number of ecophysiological model parameters (including management) was enhanced from 37 to 86.

The photosynthesis is calculated separately for sunlit and shaded canopy (de Pury and Farquhar 1997). The stomatal conductance is sensitive to CO_2 concentration according to (Medlyn et al. 2001). Maintenance respiration is a function of temperature and nitrogen concentration of plant organs (Ryan 1991). Growth respiration is set as a constant fraction of the allocation. Heterotrophic respiration is calculated as a function of temperature, water and oxygen availability. The growth of a plant compartment is a result of allocation of photosynthates minus the growth respiration and mortality rates like litterfall, residues of wood harvest and other mortality. Management of forests is taken into account through harvest and planting.

The water budget processes implemented are evaporation from canopy, stem and soil, transpiration, throughfall, snow storage and snow melt, surface runoff, infiltration, drainage, capillary rise and dynamics of the groundwater table. The nitrogen budget, based on the processes uptake, allocation, retranslocation, mineralization, denitrification, leaching with drainage, is linked to the carbon budget maintaining fixed C:N ratios of all vegetation, litter and soil pools.

The structure of the model with main compartments and carbon fluxes is described in Fig. 9. The principles of the water budget are shown in Fig. 10. An overview of input data is shown in the data flux diagram in Fig. 3.

The forest management extension contains the options thinning, clear cut, and planting including tree species changes with definable lengths of thinning periods and rotation periods. The thinning fractions may either be set by tables or can be determined from a formula whose parameters can be derived from forestry yield tables depending on the current stem carbon stock and the stand age. Derived from age-dependent biomass expansion factors (Dieter and Elsasser 2002), the logged wood stock is divided into the exported coarse wood fraction and the fine wood fraction remaining in the stand.

With the current model version, mixed stands of several vegetation units differing in tree species or tree height can be simulated according to an approach by (Bond-Lamberty et al. 2005). The calculation of the tree height from the stem carbon stock and stand density is based on species-specific parameters.

The vertical order of the canopy layers is calculated from the tree height and determines the radiation availability. Additionally, an analysis of the stand density of the layers enables a differentiation of the lower stand into covered and uncovered areas.

For the calculation of the phenological data for leaf flushing of deciduous trees or the May shoots of coniferous trees, respectively, as an additional option the model of (Menzel 1997), was implemented. This is a simplification of the model of (Cannell and Smith 1983) and computes the heat sum required for bud burst depending on the number of cold days. The timing of the litterfall period for deciduous trees can be varied by species-specific parameters depending on the day length and the number of autumnal warmth days.

The multi-layer soil water model applied is based on a capacity approach. It takes into account the vertical water flow in the soil profile. The horizons of a soil profile are split into several layers with a layer thickness of 2, 5, 10 or 20 cm. The hydrological behaviour of each horizon is defined by pore volume, field capacity, permanent wilting point and saturated hydraulic conductivity. The calculation of the infiltration and the surface runoff is based on the approach by (Holtan 1961), the percolation through the soil profile on the model of (Glugla 1969). The capillary rise from groundwater into the root zone is determined according to guidelines from the KA5 (Table 78) of the (AG-Boden 2005) taking into account the soil type and the distance to groundwater layer.

The potential evaporation and transpiration is calculated with the Penman-Monteith approach as before. The transpiration is distributed on basis of an uptake density function. The uptake density function equals the root distribution in the soil profile and is additionally reduced if the water content falls below a calculated layer dependent critical soil water content (Koitzsch 1977, Koitzsch and Günther 1990). There is the option of a simple groundwater dynamics calculation.

The distribution of the precipitation into canopy storage, stem storage and throughfall as well as the evaporation from these temporary storages has been adjusted according to van Dijk and Bruijnzeel (2001).

The implemented model for the vertical root growth is based on an approach of (Jones et al. 1991) and was modified for trees by Rasse et al. (2001). Rasse et al. (2001) specify parameters for pine and beech. In the model, the maximum root growth rate is reduced by stress factors. Of the four stress factors soil temperature, soil strength (calculated from soil density and water content), aeration and pH, the most stressful factor is determined and used to reduce the maximum root growth. The stress factors are calculated only for the horizon that contains the root tip.

The soil temperature is calculated by applying the heat transfer equation (de Vries 1963) for each soil layer down to a depth of 2 m. The temperature in the top layer is calculated with a statistical approach using the temperature of the previous day and the current day's air temperature, radiation balance, crown cover and evaporation. The initialization and calculation of the seasonal temperature pattern in 2.5 m depth as lower boundary condition is based on Krenz (1943), cited in Hoffmann et al. (1993).

To better take into account the influence of soil moisture on the decomposition, a restriction for relative water contents greater than 60% (based on the pore volume) was implemented according to Freytag and Lüttich (1985). Below this water content the decomposition rate increases log-linearly with increasing soil water potential as before. At water contents above 60%, a log-linear limitation of the decomposition rate takes place reflecting the conditions of increasing oxygen deficiency. In addition, the decomposition rate is restricted by limited oxygen availability with increasing soil depth and clay content according to Franko (1997).

The multi-layer approach is applied to the soil carbon and nitrogen pools with each four soil pools and one coarse and one fine root pool for every soil layer (Fig. 9). The coarse woody debris (CWD) pools of the original version were split up into one aboveground stem CWD pool and one root CWD pool for each soil layer. In analogy, the litter layer pools of the original version were split up into one leaf litter pool and one fine root pool for each soil layer.

For all following chapters of the report, each time the model Biome-BGC is mentioned, the actual version Biome-BGC (version ZALF) is meant.

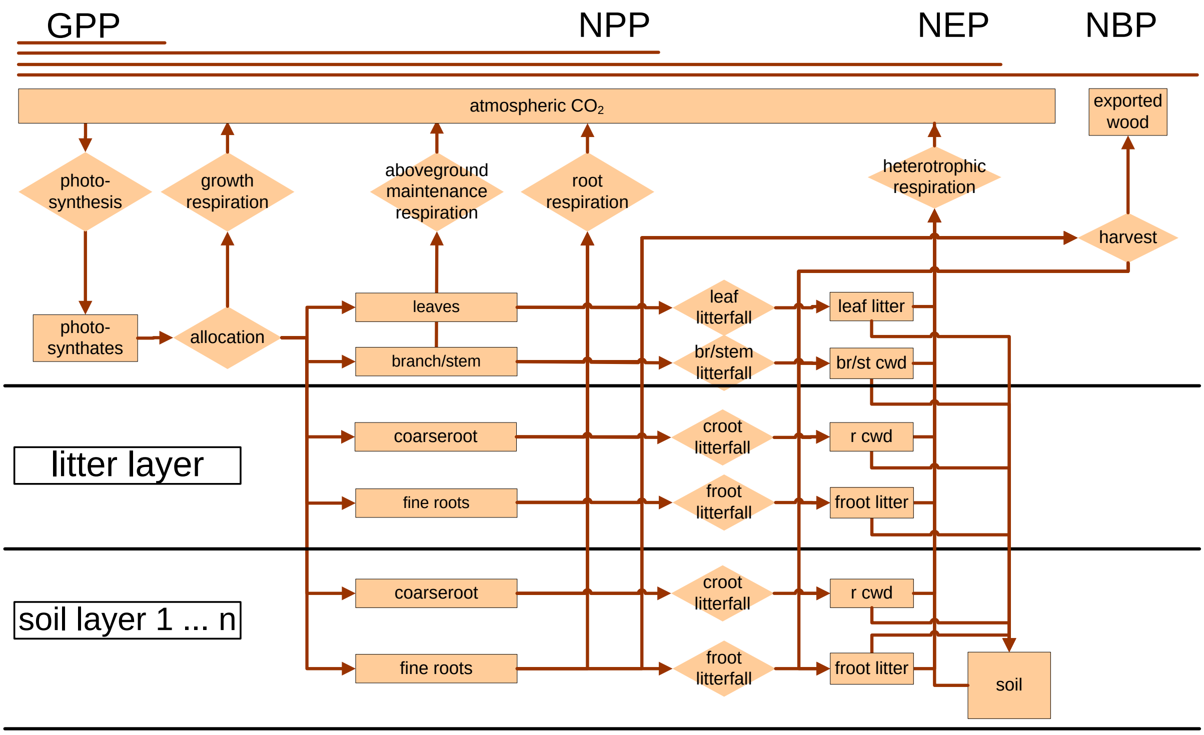


Fig. 9 Compartments of carbon pools in the model Biome-BGC (version ZALF)

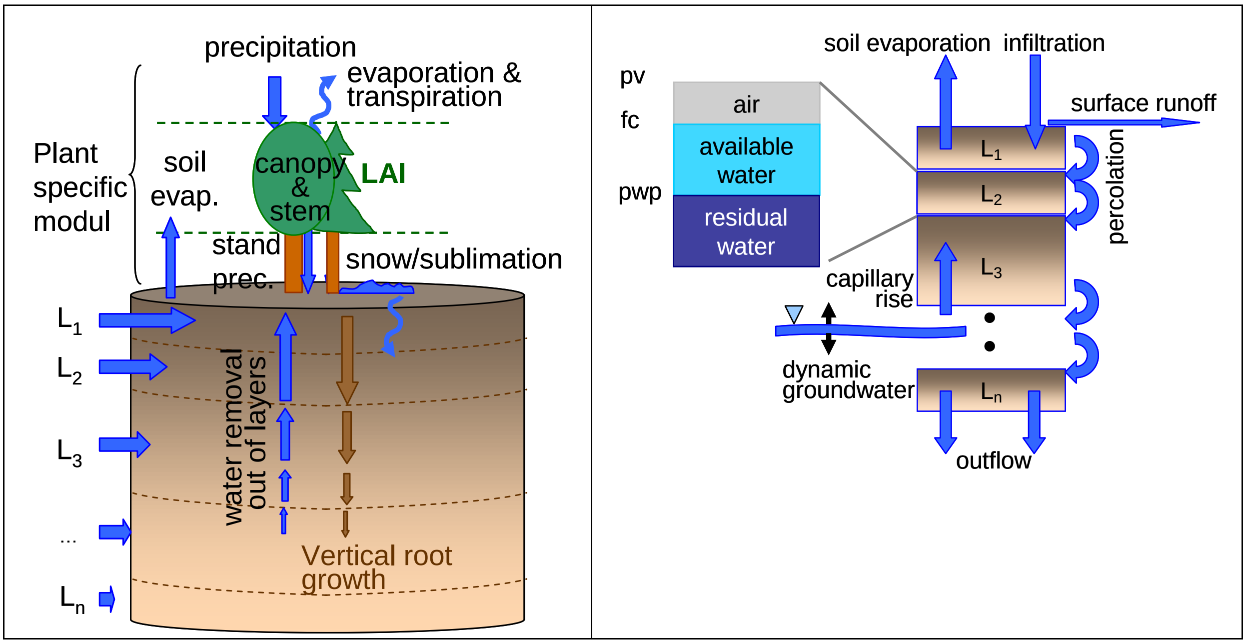


Fig. 10 Schematic diagram of water fluxes (left) and the capacity approach of the soil water module (right) of Biome-GBC (version ZALF)

2.4 Scenario simulation setup

For the calibration run, the simulation start was determined by the first year with measurements on stem carbon available. In case of measurements starting later than 1990, which applies for most plots, a ten years pre-simulation period was introduced in order to reduce model inherent trends during the calibration period before the actual simulation starts. The simulation end was 2009 or 2010 depending on the availability of meteorological data. For details on applied simulation periods see Tab. 3.

For the investigation of the climate change effects a reference period and two future periods were defined. The reference period equals the calibration period mentioned above keeping initial values, model parameters, and N deposition, but uses instead of measured data the climate data and CO_2 concentration of the FutMon_CLM dataset (C20/A1B or C20/B1) described in chapter 2.2.1.1. For future periods this reference period was shifted by 50 and 90 years using the climate data originated from the A1B or B1 scenarios.

For comparability of the plotwise simulation results the periods were truncated to 1996-2009 for the calibration period and 1990-2009, 2040-2059, and 2080-2099 for the reference and future simulation periods.

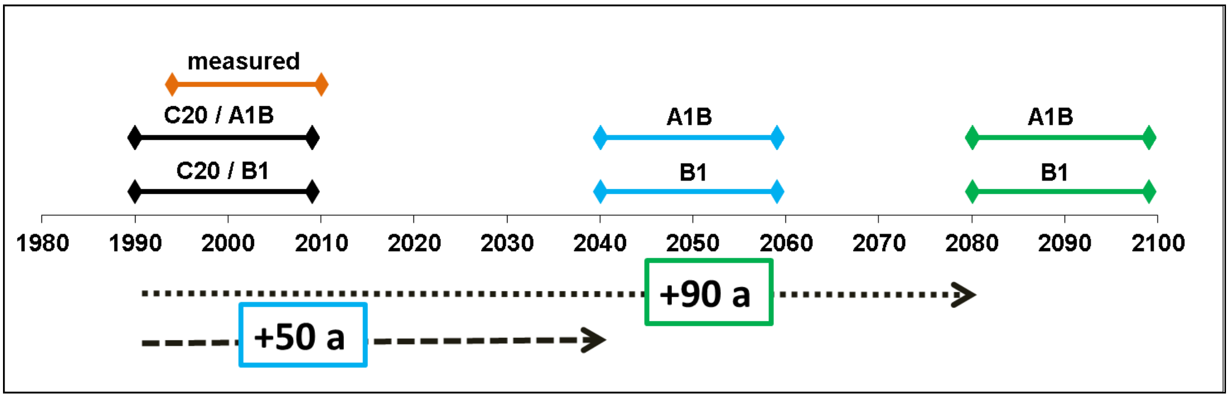


Fig. 11 Schematic diagram of the time scales of simulation periods for the calibration period using measured meteorology, and the climate change projections with the reference period of the past and two future periods

Tab. 3 Start and end of calibration periods of the plots and origin of meteorological data used for pre-simulation period

Plot	start pre-simulation	start simulation	end simulation	origin of meteorological data for pre-simulation period
AT0016	1984	1994	2010	NCEP/NCAR + E-OBS
BE0015	1986	1996	2010	NCEP/NCAR + E-OBS
DE0301	1989	1999	2009	copy of first 10 years
DE0302	1987	1997	2009	copy of first 10 years
DE0303	1987	1997	2009	copy of first 10 years
DE0304		1976	2009	-
DE0305		1976	2009	-
DE0307	1984	1994	2009	copy of first 10 years
DE0308		1978	2009	-
DE0901	1986	1996	2010	copy of first 10 years
DE0908	1986	1996	2010	copy of first 10 years
DE0919	1986	1996	2010	copy of first 10 years
DE1201	1967	1996	2009	STAR (Orlowsky 2007)
DE1202	1967	1996	2009	STAR (Orlowsky 2007)
DE1203	1967	1996	2009	STAR (Orlowsky 2007)
DE1204	1967	1996	2009	STAR (Orlowsky 2007)
DE1205	1967	1996	2009	STAR (Orlowsky 2007)
DE1206	1967	1996	2009	STAR (Orlowsky 2007)
GR0002	1984	1994	2010	NCEP/NCAR + E-OBS
IT0001	1986	1996	2010	NCEP/NCAR + E-OBS
IT0006	1986	1996	2010	NCEP/NCAR + E-OBS
IT0008	1986	1996	2010	NCEP/NCAR + E-OBS
IT0009	1986	1996	2010	NCEP/NCAR + E-OBS
IT0010	1987	1997	2010	NCEP/NCAR + E-OBS
IT0012	1989	1999	2010	NCEP/NCAR + E-OBS
IT0017	1987	1997	2010	NCEP/NCAR + E-OBS
SK0206	1989	1999	2010	NCEP/NCAR + E-OBS
SK0209	1989	1999	2010	NCEP/NCAR + E-OBS

3 Results

3.1 Model calibration results

Comparison of simulation results with measured data demonstrate, that the simulation model allows a more or less precise simulation of water and carbon budgets.

In the following sections, simulation results are presented in comparison to existing field measurements. The measured elements of the water and carbon balance are presented exemplarily for different plots. For comparison of simulation results, both the measured data of the level II database and the data provided by the German forest research institutes were used. In some cases they differ and are presented separately if necessary.

The comparison of simulated with measured elements of the water and carbon budget for all investigated plots will be provided on request.

3.1.1 Soil temperature

Since soil temperature is one of the most important factors for decomposition processes in soils, its correct simulation, at least for soil depths rich in organic carbon, is a precondition for valid simulations on carbon budget of forests. The model simulates the soil temperature for soil depths down to 250 cm.

The visual comparison of the simulation results shows a rather good agreement with measured data (Fig. 12). Larger differences with a higher amplitude of measured data during 2005 – 2009 of the example are probably caused by a strong harvest in winter 2004/05.

For the estimation of the correlation coefficients, the data of all soil depths were classified into the depth classes 0 – 20 cm, 21 – 40 cm, 41 – 80 cm, and > 80 cm. The correlation coefficients (R^2) between the daily simulated and measured values were with one exception within each depth class and plot above 0.9, in average 0.967 ± 0.022 with no significant differences between the depth classes. The correlation coefficient between the plotwise means of the simulated versus measured soil temperature gives values of 0.955, 0.974, 0.972, and 0.965 for the above mentioned depth classes. The inclination of the regression line is 1.000 for all depth classes. Larger deviations between measured and simulated soil temperature occur in 1 cm soil depth in the winter months, but probably do not have large effects on processes related to the carbon budget.

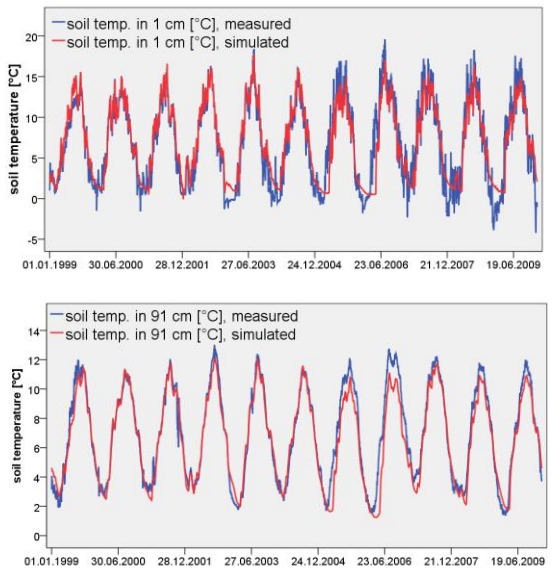


Fig. 12 Comparison of simulated with measured soil temperature for plot DE0305 at different soil depths

3.1.2 Phenology and leaf area index

The length of the vegetation period, expressed as difference between leaf flushing and litterfall, as well as the leaf area index (LAI) are key parameters in process based carbon budget models, as the water fluxes and gas exchange processes like interception, transpiration, and CO_2 diffusion into leaves are determined by the duration of the leaved period and the extent of leaf area.

Main water and CO_2 exchange processes with the atmosphere take place in the forest canopy. The interception and the photosynthetic efficiency are direct functions of leaf area index (LAI). For this reason, the correct simulation of LAI and its seasonal dynamic are essential for the simulation of water, carbon and energy budgets in biogeochemical simulation models.

The simulated values of leaf area index as well as the variation of leaf flushing and litterfall period are shown for a deciduous tree species with short leaf unfolding and litterfall periods and a coniferous forest with low seasonal amplitude of leaf area index (Fig. 13, left). The measured LAI values differ widely depending on the source of data and the methods used. The sharp decrease in annual maximum LAI in 2005 for both forest stands depicted is caused by strong harvests in the autumn 2004. The start and end points of the vegetation period could be calibrated using measured data (Fig. 13, right).

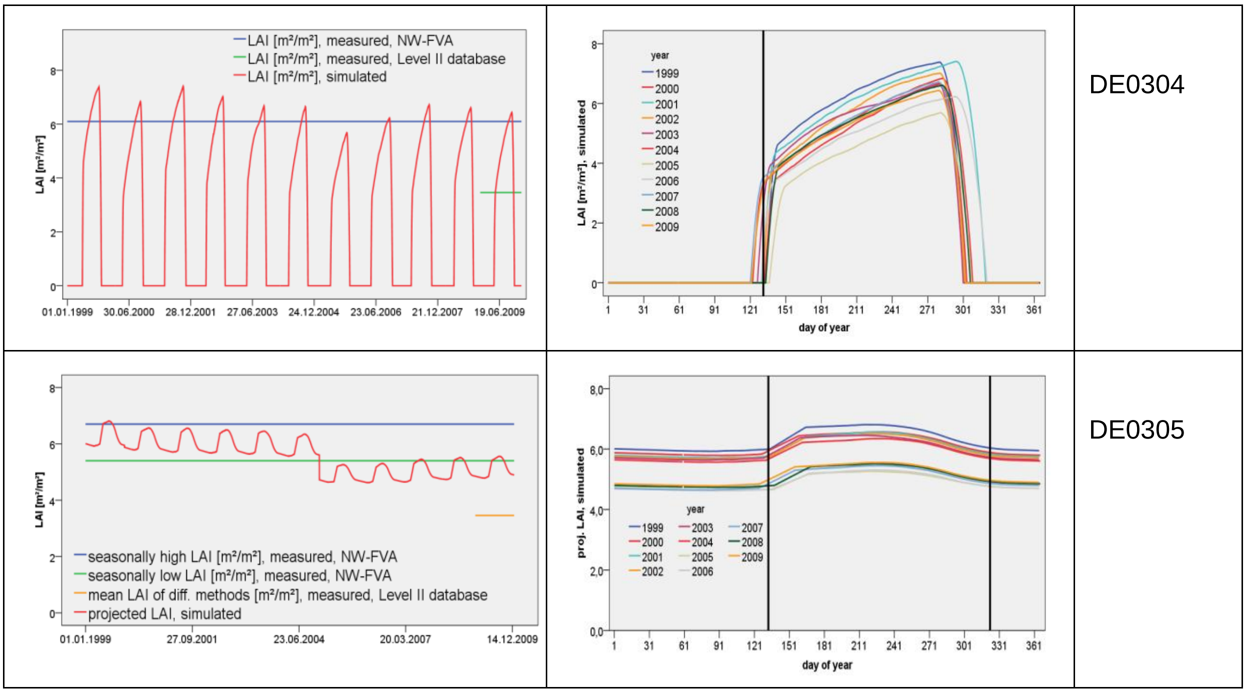


Fig. 13 Comparison of simulation results with measured data for the LAI (left) and begin and end of the vegetation period (right) on plots DE0304 (Solling beech) and DE0305 (Solling spruce). Black vertical lines indicate measured leaf flushing and litterfall dates.

3.1.3 Water budget

Because of bidirectional interdependencies between the water and carbon budgets of terrestrial ecosystems the correct simulation of the water budget is a substantial precondition for valid simulations of carbon budgets with process based models. Both, the carbon assimilatory and the respiratory sub-processes can be limited by reduced water availability, but also by excess soil water. For this reason the results of model calibration for some sub-processes of water budget like stand precipitation, transpiration, and soil moisture development are shown.

3.1.3.1 Throughfall and canopy evaporation

The distribution of bulk precipitation into canopy evaporation and stand precipitation, that is the sum of throughfall and stemflow, if applicable, affects the available water for the whole ecosystem processes including the carbon budget turnover. It is strongly determined by the seasonal dynamic of precipitation and on the development of leaf area as a limiting variable of canopy evaporation.

The results show, that a rather good agreement of simulated and measured stand precipitation can be achieved, while the simulated canopy evaporation deviates stronger from the measurements. The plotwise correlation coefficients of simulated versus measured data results in values of 0.678 ± 0.156 for stand precipitation and in 0.320 ± 0.170 for canopy evaporation. Comparing the annual sums of the simulated versus measured data leads to a correlation coefficient of 0.812 ± 0.173 for the stand precipitation and of 0.427 ± 0.371 for the canopy evaporation. The plotwise means of both the canopy evaporation and the stand precipitation are almost perfectly met.

Major deviations between simulated and measured data occur during wintertime, when precipitation is partly stored as snow in the canopy and is measured later as stand precipitation during snow melt. Snow storage in the canopy cannot be simulated by the model.

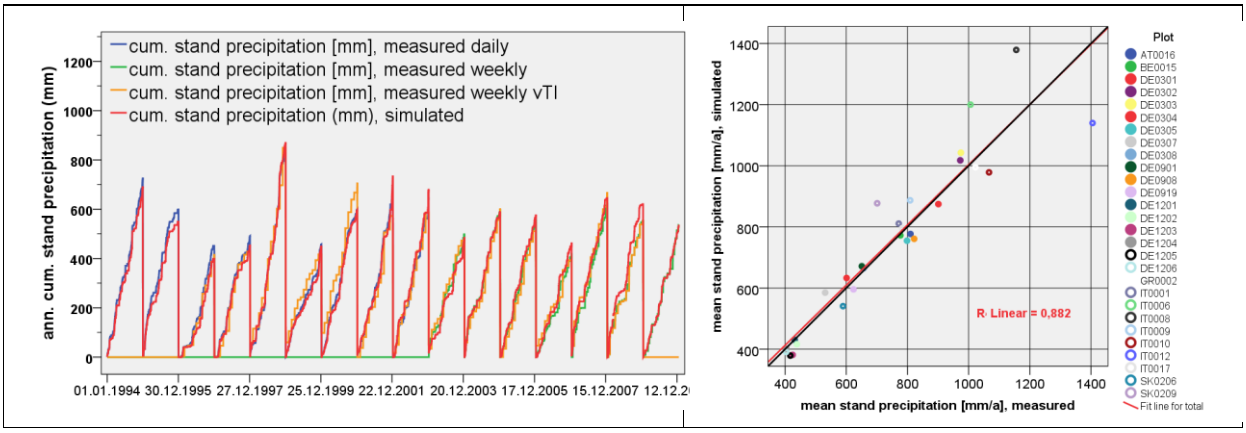


Fig. 14 Comparison of simulation results with measured data of annually cumulated stand precipitation for plot DE0307 (left) and simulated vs. measured stand precipitation including regression line over 28 plots

3.1.3.2 Transpiration

Although it is a very important indicator for stomatal conductance and its regulatory environmental conditions, measured transpiration data are available for three stands only. An example for simulated and measured daily stand transpiration is shown in Fig. 15.

In general, the correlations are classified as good (R^2 = 0.680 for DE0304, 0.797 for DE0305 and 0.721 for DE1202). Especially in the summer months of July and August 1996, there is an underestimation of the transpiration for both plots. At the plot DE0305, the transpiration is underestimated in winter 2003/2004 and overestimated in summer 2004. On average the transpiration rate is overestimated by 12 %.

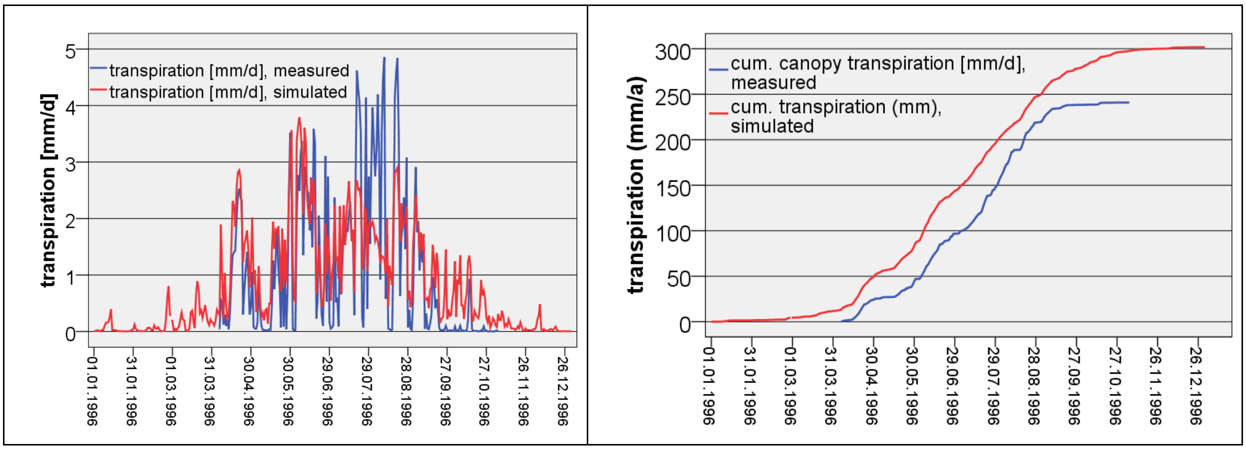


Fig. 15 Comparison of simulation results with measured data of daily transpiration (left) and cumulative annual transpiration (right) of the Solling spruce stand (plot DE0305) during the year 1996

3.1.3.3 Soil moisture

The seasonal variation of soil water content is used for the calibration of soil water processes like soil water percolation, evaporation, and uptake for transpiration. Soil moisture is measured by TDR probes in one or several soil depths at many level II plots and can be compared with simulated values. At some plots, soil moisture is available only by calculating it from measured soil matric potential using measured soil water retention curves or by applying pedotransfer functions. The water contents from the TDR probes were preferably used for calibration.

The model output offers water content of distinct soil depths. In analogy to the soil temperature we built soil layer classes for the statistical analysis. For the upper layers usually a better model performance is achieved than for the lower ones. For the soil layer classes 0 – 20 cm, 21 – 40 cm, 41 – 80 cm, and > 80 cm, plotwise correlation coefficients of 0.685 ± 0.124, 0.650 ± 0.150, 0.618 ± 0.212, and 0.405 ± 0.351 were calculated. The regression lines of the simulated versus measured plot means have inclinations of 0.983, 0.860, 0.984, and 0.926 for the above mentioned depth classes indicating a considerable underestimation of the water contents in the layer in 21 – 40 cm depth. The correlation coefficients of the plotwise means for the soil layers are 0.884, 0.704, 0.976, and 0.904.

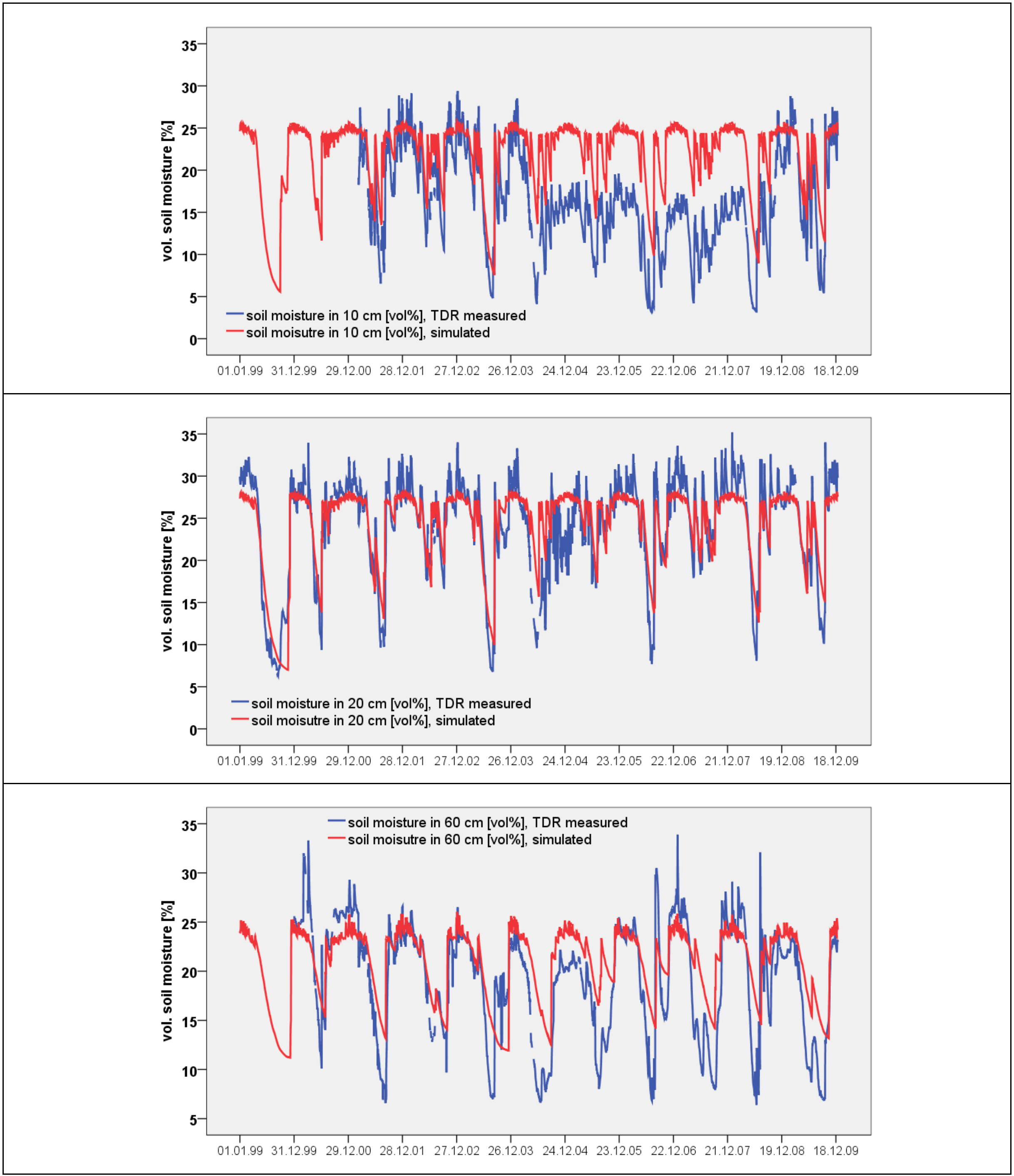


Fig. 16 Comparison of simulation results for the volumetric water content on plot DE0307 in different soil depths with measured data obtained from TDR-probes

3.1.4 Carbon budget

A large number of level II plots offer measured data for the calibration of dynamic simulation models on the carbon budget of forest ecosystems. Time series of several carbon fluxes like stem growth, litterfall, and soil respiration or pools like stem, litter, and soil carbon in different ecosystem compartments are analysed.

3.1.4.1 Stem carbon stocks and increment

Stem wood is one of the largest carbon sinks in forest ecosystems and provides one of the main carbon stocks, at least in mature forests.

Tree growth is measured in inventories with steps of at least 5 years at nearly all level II plots. During the FutMon project additional analyses of tree growth with higher temporal resolution were started. Tree ring analyses may help to resolve the tree growth to annual data, whereas girth band measurements provide data on seasonal dynamics of stem growth. In this project the data from inventories were used for model calibration, only.

At most of the plots presented here at least four inventories with three 5 years steps from 1994 to 2009 were conducted leading to at least three tree growth estimates. An example of simulated in comparison to measured carbon stocks of the remaining stem, the cumulative harvested, and the sum of both over a simulation period of 34 years is shown in Fig. 17 for plot DE0304. The differences of measured tree carbon stocks were transformed to averages of annual tree growth rates over the time steps and compared to simulated annual tree growth.

The plotwise averages of these values of all simulated plots show, that the simulation model can be calibrated using these measured data, even if we slightly underestimate tree growth in case of higher rates (Fig. 18). The regression line is close to the 1:1 line ($R^2 = 0.967$). But looking at the stem growth rates of the 5-years periods, the time series of measured data are met only occasionally by the simulations and show correlation coefficients of 0.123±0.572 containing some negative values as well.

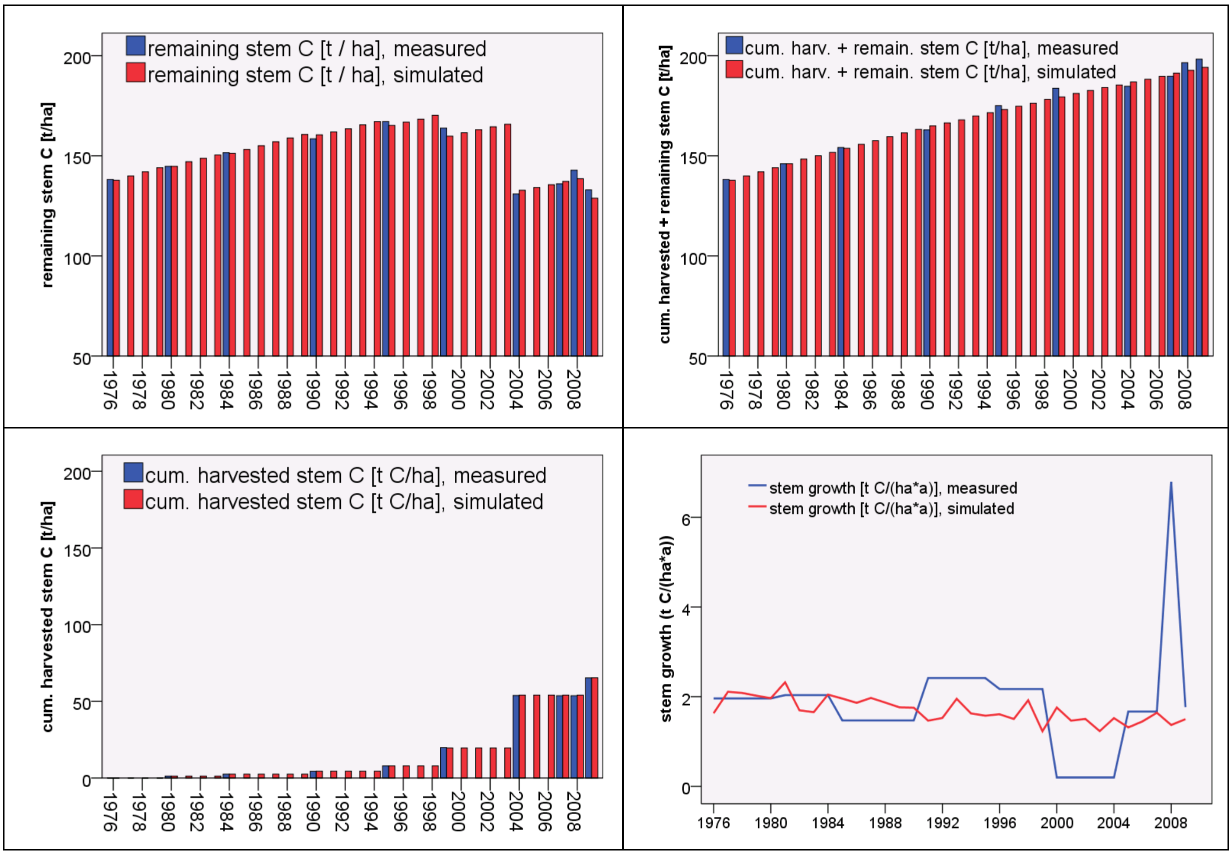


Fig. 17 Comparison of the simulation result with measured data on the remaining stem carbon stocks, the cumulative harvested stem C, the sum of remaining and cumulative harvested stem C, and the stem growth rate

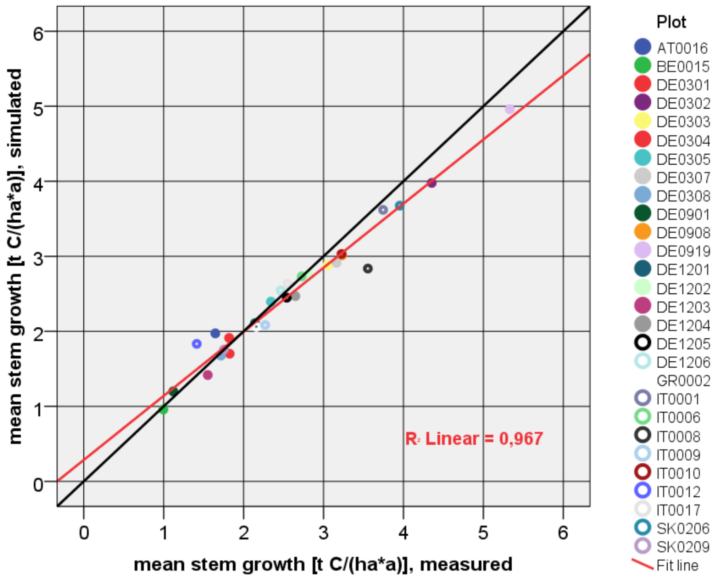


Fig. 18 Measured vs. simulated plotwise means of stem growth including regression line over 28 plots

3.1.4.2 Litterfall

Measurement of litterfall has been optional at the beginning of the ICP Forests level II program, but was started at a larger number of plots during the FutMon project. For many plots, measured data on litterfall of different fractions are available on an annual basis, but often for one year, only.

Litterfall rates play an important role for modelling of carbon balance, because on one hand, litterfall is a significant carbon flux in the forest ecosystem and on the other hand, it is a valuable basis for LAI calculation.

One example for model calibration against measured leaf litterfall shows, that the simulated values fit to the measured ones, but with a lower annual variation (Fig. 19). The strong decrease in 2002 is caused by a preceding harvest and can be simulated similar to the observed data.

Biome-BGC differentiates aboveground litterfall into fractions of foliage and wood, whereas fruits and flowers are not explicitly simulated. In order to simulate correct carbon fluxes in litterfall, the contribution of fruits and flowers have to be included in the wood litterfall. The example for simulated stem vs. measured wood+fruit litterfall shows, that in contrast to the observed wood and fruit litterfall the simulated wood litterfall only shows a very low annual variation (Fig. 19, bottom).

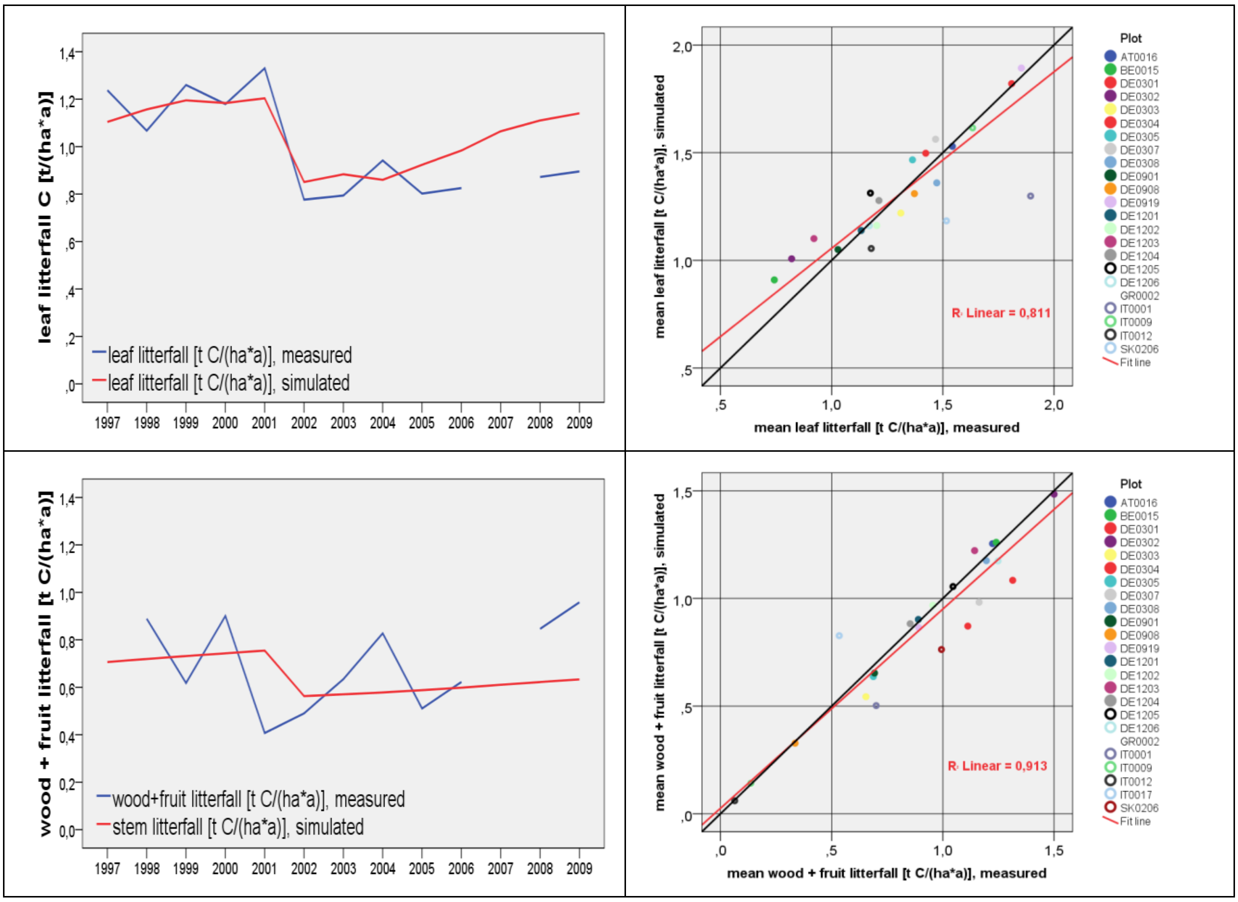


Fig. 19 Measured vs. simulated litterfall of leaf litter (upper left) and wood+fruit litter (lower left) of plot DE0307 and the regression between measured vs. simulated averages of leaf and wood+fruit litterfall over 28 plots (right)

A comparison of simulated vs. measured leaf litterfall shows a slight overestimation of the simulation results on leaf litterfall in case of low leaf litterfall rates, and a small underestimation of wood+fruit litterfall of stands with high rates. The correlation coefficient of the plotwise means of measured versus simulated values is 0.811 for leaf litterfall and 0.913 for wood + fruit litterfall.

3.1.4.3 Soil organic carbon

The soil organic carbon (SOC) of organic layer and mineral soil is an important storage compartment for carbon in forest ecosystems. Time series of the SOC of the level II plots would be a useful indicator for the assessment of source-sink relationships of forest ecosystems. But in our dataset those values were available only for the two Solling plots (DE0304, DE0305).

The measured values of soil organic carbon of plot DE0304 show high temporal and spatial (not shown) variability in the organic layer and mineral soil without any clear trend. The model simulated a rising trend in organic layer and a decreasing one in mineral soil down to 50 cm depth. A satisfying model calibration close to the measured SOC could not be achieved for these plots.

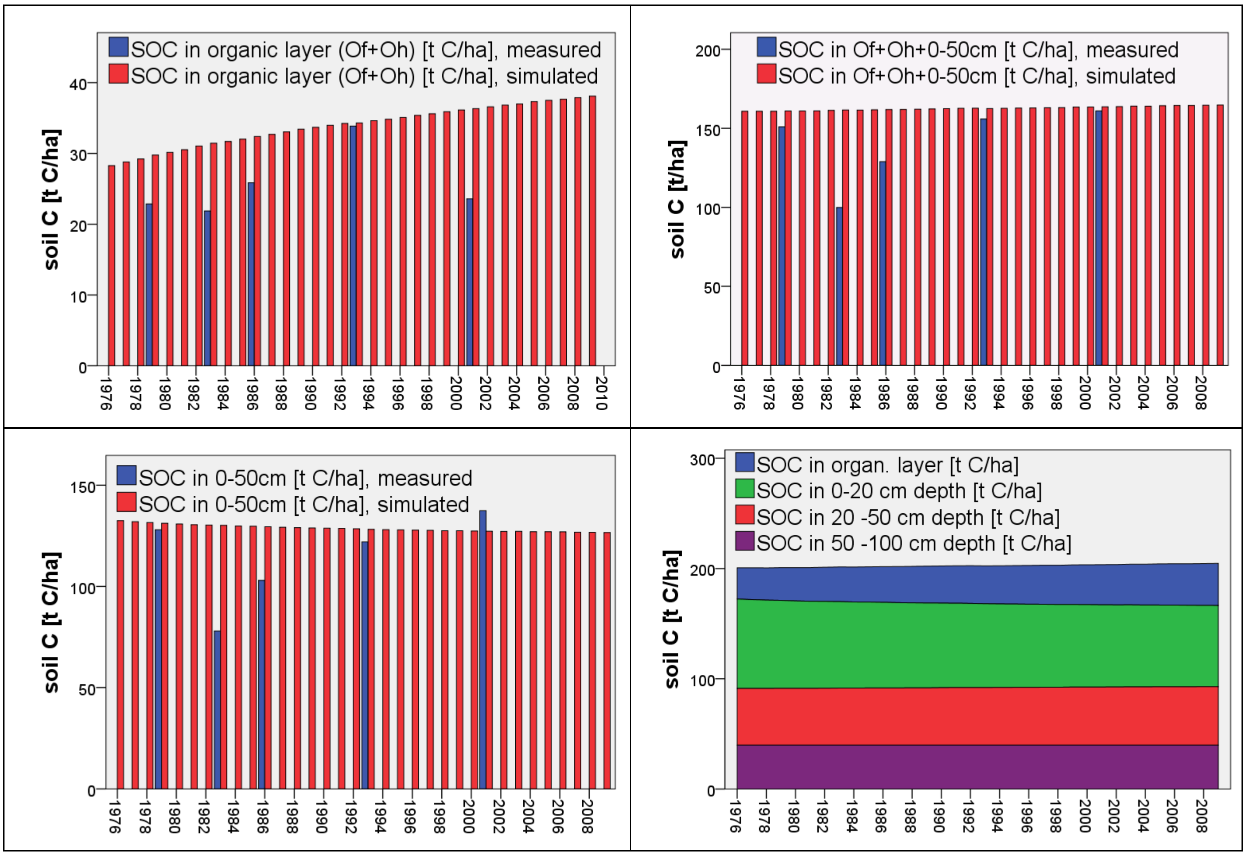


Fig. 20 Comparison of simulated with measured data of soil organic carbon (SOC) of the organic layer and the upper 50 cm of mineral soil of plot DE0304 and development of simulated SOC in different soil layers down to 100 cm depth

3.1.4.4 Soil respiration

Measurements of soil respiration are not part of the ICP Forests level II program, but were conducted during a ForestFocus project at some German level II plots and continued until today, partly. The trenching technique was applied for the differentiation of autotrophic and heterotrophic parts of the soil respiration.

In the shown example of plot DE0908 the simulation model represents the measured soil respiration more or less precisely with an overestimation during winter time and an underestimation during some extreme summer events (Fig. 21). But there are systematic deviations between measured and simulated values of the two fractions. Whereas the model simulated too high heterotrophic respiration, the root respiration was underestimated. During the calibration procedure it was not possible to achieve better correlations with realistic model parameters that determine the root respiration. The mean simulated vs. measured soil respiration over all 15 plots with available data does not correlate at all (Fig. 22).

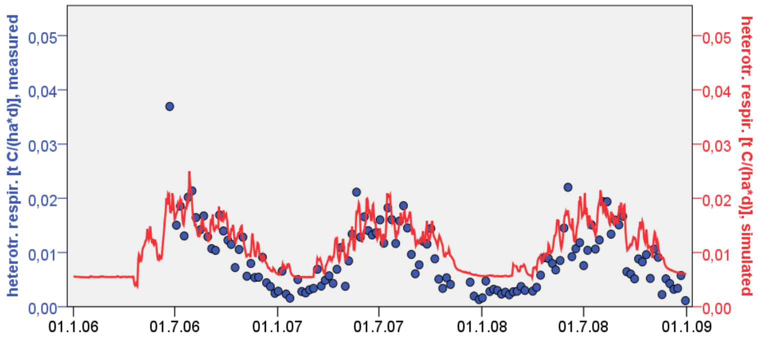
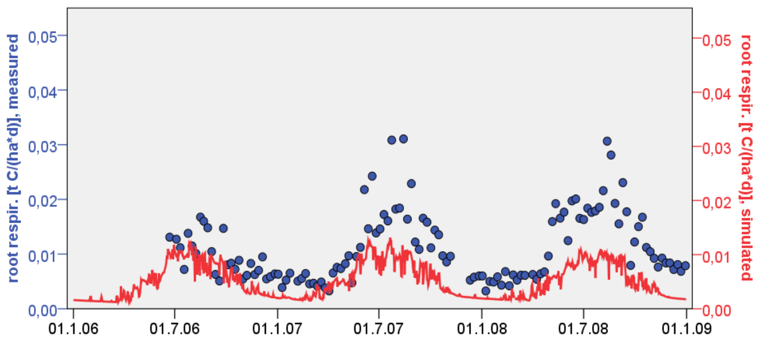
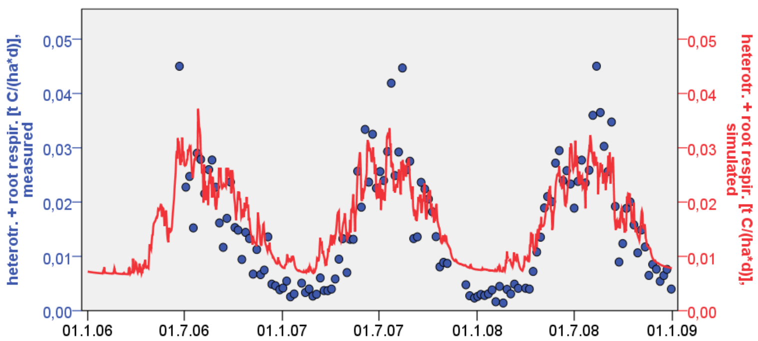
	**heterotrophic respiration**
	**root respiration**
	**soil respiration**

Fig. 21 Comparison of simulated with measured data of heterotrophic respiration, root respiration and the sum of both, the soil respiration on plot DE0908

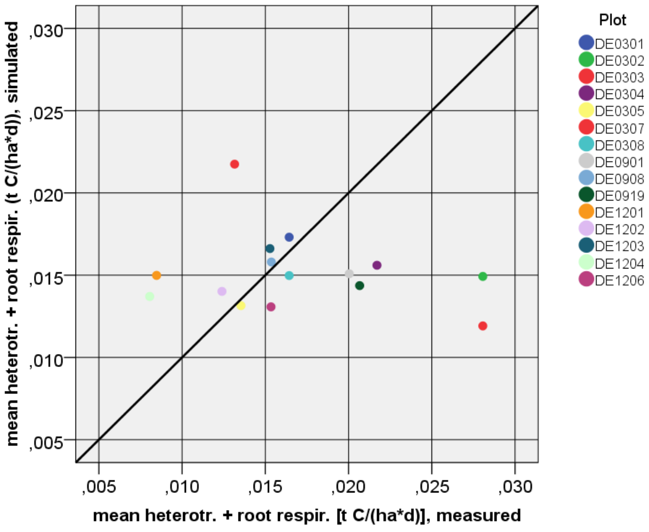


Fig. 22 Comparison of simulation results and measured values of the soil respiration of all 15 plots with available data

3.2 Simulation results under current climate

The carbon balance of forest ecosystems is expressed by different aspects, for example by investigating the distribution of carbon stocks over the ecosystem compartments, by describing the relations of allocation of photosynthates to the plant compartments, and by analysing the carbon sinks in terms of carbon losses and changes of carbon pools.

3.2.1 Carbon stocks

As an overview, the carbon stocks of the investigated forest ecosystems are presented in Fig. 23. For the year 2009, in our simulations on average a total carbon stock of 323 t C ha^{-1} was calculated with the main fractions in soil down to 100 cm depth (152 t C ha^{-1} = 47 %) and stem, branch and twigs wood (125 t C ha^{-1} = 39 %), followed by leaf+root litter including coarse woody debris (22 t C ha^{-1} = 6.9 %), coarse roots (18 t C ha^{-1} = 5.4 %), needle/leaves (3.9 t C ha^{-1} = 1.2 %), and fine roots (1.8 t C ha^{-1} = 0.6 %) (Tab. 4).

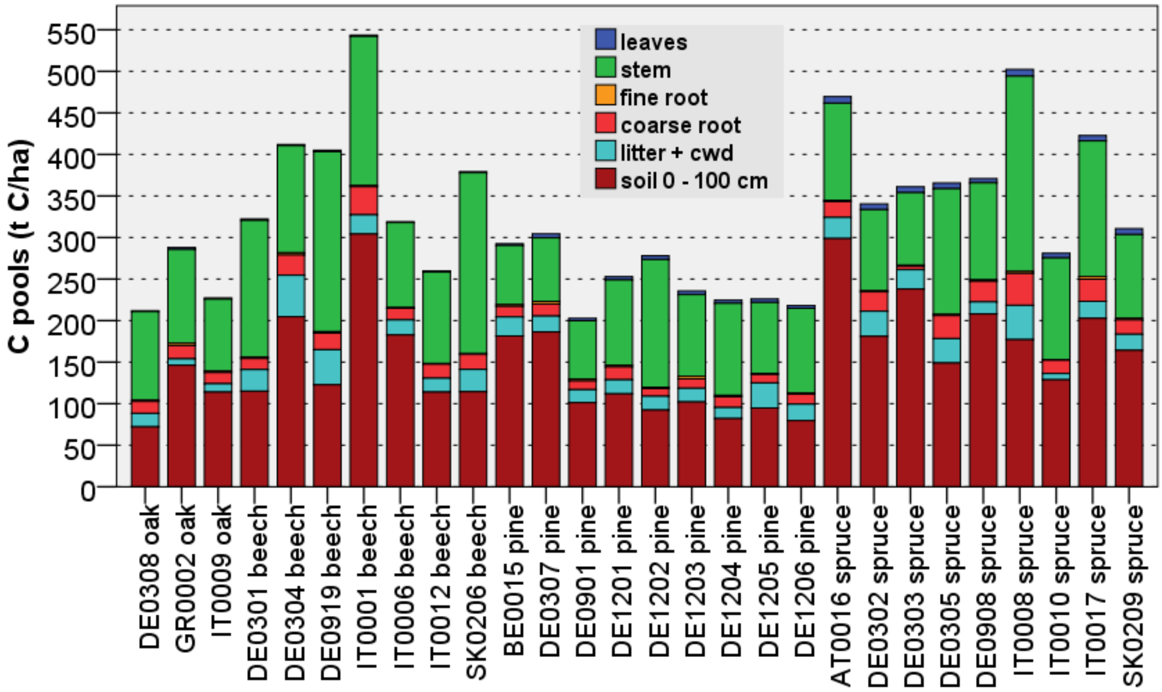


Fig. 23 Carbon pools (t C ha^{-1}) of forest ecosystems at level II plots as simulated for 2009 using measured climate data. Soil carbon includes humus layer and mineral soil (0 - 100 cm).

Tab. 4 Carbon pools (t C ha^{-1}) of forest ecosystems at level II plots in 2009 using measured climate data. Soil carbon is limited to 100 cm soil depth.

Plot	Species	Leaf (ann. max.)	Stem + branch wood	Fine root	Coarse root	Leaf litter	Fine root litter	Coarse woody debris	Soil (0-100 cm)	Total
AT0016	spruce	8.11	116.7	1.70	19.0	2.80	3.09	19.6	298.7	469.7
BE0015	pine	2.11	71.3	2.22	12.5	0.87	3.18	19.0	181.4	292.6
DE0301	beech	1.66	164.7	1.64	13.2	2.08	11.90	12.0	115.1	322.4
DE0302	spruce	6.91	97.7	1.26	23.2	2.04	5.08	23.2	181.0	340.5
DE0303	spruce	7.22	87.2	1.26	4.3	1.35	9.45	12.5	237.9	361.2
DE0304	beech	1.33	128.9	2.86	24.3	3.16	26.25	20.6	204.6	411.9
DE0305	spruce	6.94	151.3	1.43	27.7	1.60	11.86	15.9	148.9	365.6
DE0307	pine	4.96	76.5	2.98	14.7	1.21	2.97	14.9	186.3	304.5
DE0308	oak	1.24	106.6	1.49	14.3	2.10	2.85	11.3	72.2	212.0
DE0901	pine	2.86	70.3	2.19	10.5	1.00	1.39	13.2	101.3	202.7
DE0908	spruce	4.99	116.9	1.66	24.8	0.85	3.08	10.7	207.9	370.9
DE0919	beech	1.82	216.5	1.62	20.0	3.59	28.20	10.6	122.7	405.1
DE1201	pine	3.93	102.8	2.06	15.4	1.05	1.28	14.4	112.0	252.9
DE1202	pine	4.61	153.7	1.70	9.1	1.61	2.29	12.9	92.2	278.1
DE1203	pine	4.30	98.5	2.98	11.3	1.33	1.61	13.7	102.1	235.7
DE1204	pine	3.60	110.8	1.81	12.8	1.27	1.62	10.5	82.1	224.5
DE1205	pine	4.14	85.3	1.36	10.1	4.35	3.24	22.7	94.7	226.0
DE1206	pine	3.38	102.1	1.23	12.1	2.71	2.90	14.2	79.6	218.2
GR0002	oak	2.40	113.0	2.58	16.1	1.93	2.63	3.1	146.3	288.0
IT0001	beech	1.26	179.6	1.45	33.8	1.71	9.02	12.5	304.2	543.5
IT0006	beech	1.08	102.2	0.93	13.9	2.36	8.53	7.3	182.7	319.1
IT0008	spruce	7.99	235.0	2.43	38.6	2.36	24.56	14.1	177.2	502.3
IT0009	oak	1.50	86.7	1.60	13.6	1.71	4.64	3.7	113.9	227.4
IT0010	spruce	5.64	122.2	0.92	16.1	0.72	3.19	3.6	128.7	281.0
IT0012	beech	1.05	110.2	0.93	16.7	3.25	8.24	5.1	114.2	259.6
IT0017	spruce	6.51	163.3	3.13	26.6	4.03	2.95	13.6	202.7	422.7
SK0206	beech	1.15	217.7	0.97	18.0	2.18	14.41	10.4	114.3	379.2
SK0209	spruce	6.40	117.6	1.95	19.1	1.17	11.36	8.4	162.2	328.2
Average		3.90	125.2	1.80	17.6	2.01	7.56	12.6	152.4	323.1

3.2.2 Carbon allocation to plant compartments

The photosynthetic carbon fixation by trees of the investigated plots amounts to an average of 14.3 t C ha^{-1} a^{-1}. 44 % of the photosynthates are allocated to the needles/leaves (including a 19 % fraction immediately consumed by light respiration), 32 % to the aboveground wood, 18 % to fine roots, and 7 % to coarse roots (Fig. 24). The allocation pattern presented is a result of the model parameters for allocation that had to be adapted during the calibration procedure to fit to the observed wood growth as well as leaf, wood, and fruit litterfall rates. It has to be pointed out that the allocation rates do not equal to the growth rates of the compartments. In order to obtain net growth rates, plant respiration and litterfall rates have to be taken into account.

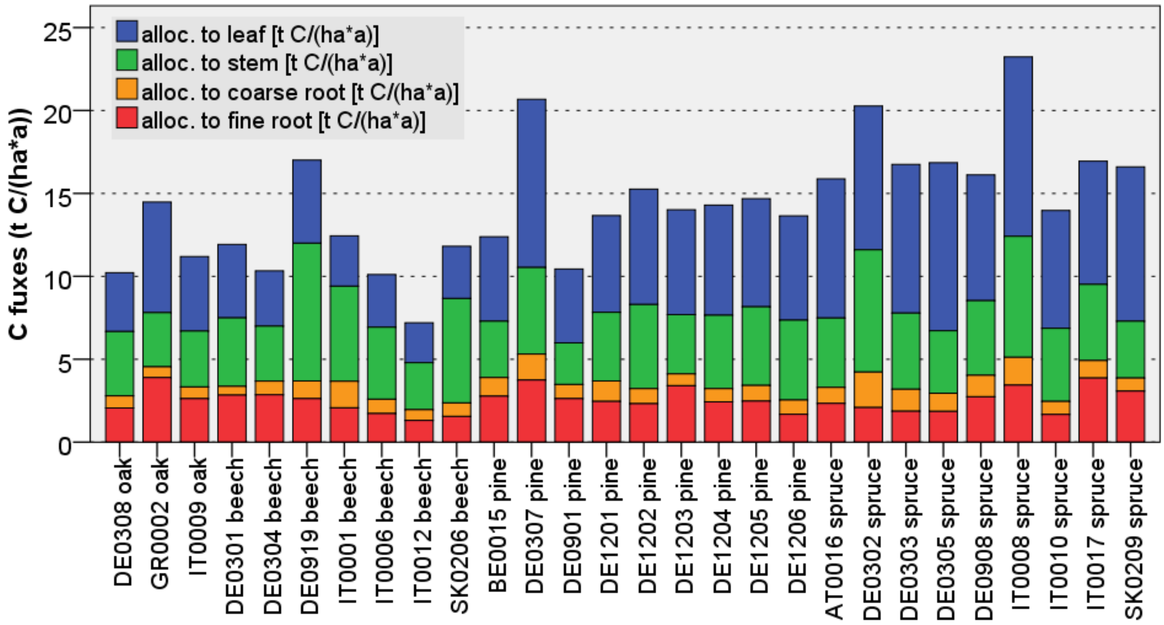


Fig. 24 Simulated carbon allocation to plant compartments of forest ecosystems at level II plots between 1996 and 2009

3.2.3 Carbon losses and carbon sinks in the ecosystem

The produced biomass is turned over and contributes to the litter, coarse woody debris, and finally via decomposition to soil organic matter. The carbon balance can be expressed in terms of processes, by which the carbon leaves the ecosystem or is stored in different compartments (Fig. 25, Tab. 5, Tab. 6). In terms of carbon balance the rate of photosynthesis is called gross primary production (GPP) and for the 28 level II plots is simulated to a rate of 14.3 t C ha^{-1} a^{-1}. The plant respiration, averaging 53 % of the GPP, is the largest process of carbon losses in the forests, with the maintenance respiration (39 % of GPP) as the higher and growth respiration (14 %) as the lower part. The rest (6.7 t C ha^{-1} a^{-1} = 47 % of GPP) amounts to the net primary production (NPP), that is regarded as short term carbon balance. 28 % (= 4 t C ha^{-1} a^{-1}) of the fixed carbon is lost in the process of heterotrophic respiration, leading to a net ecosystem production of 2.7 t C ha^{-1} a^{-1} as the medium term carbon balance for the plots evaluated. Taking into account the rate of exported carbon by harvest (0.91 t C ha^{-1} a^{-1} = 6.4 % of GPP) results in an average value of 1.8 t C ha^{-1} a^{-1} (= 13 % of GPP) for the net biome production (NBP), that is seen as the long term carbon balance. The NBP corresponds to the sum of annual change rates of the carbon pools in vegetation (1.47 t C ha^{-1} a^{-1}), leaf and fine root litter (0.26 t C ha^{-1} a^{-1}), coarse woody debris (0.14 t C ha^{-1} a^{-1}), and soil organic matter (-0.07 t C ha^{-1} a^{-1}). Depending on the situation at the beginning of the simulation period and on the harvest the NBP can become a negative or a positive value (Fig. 26).

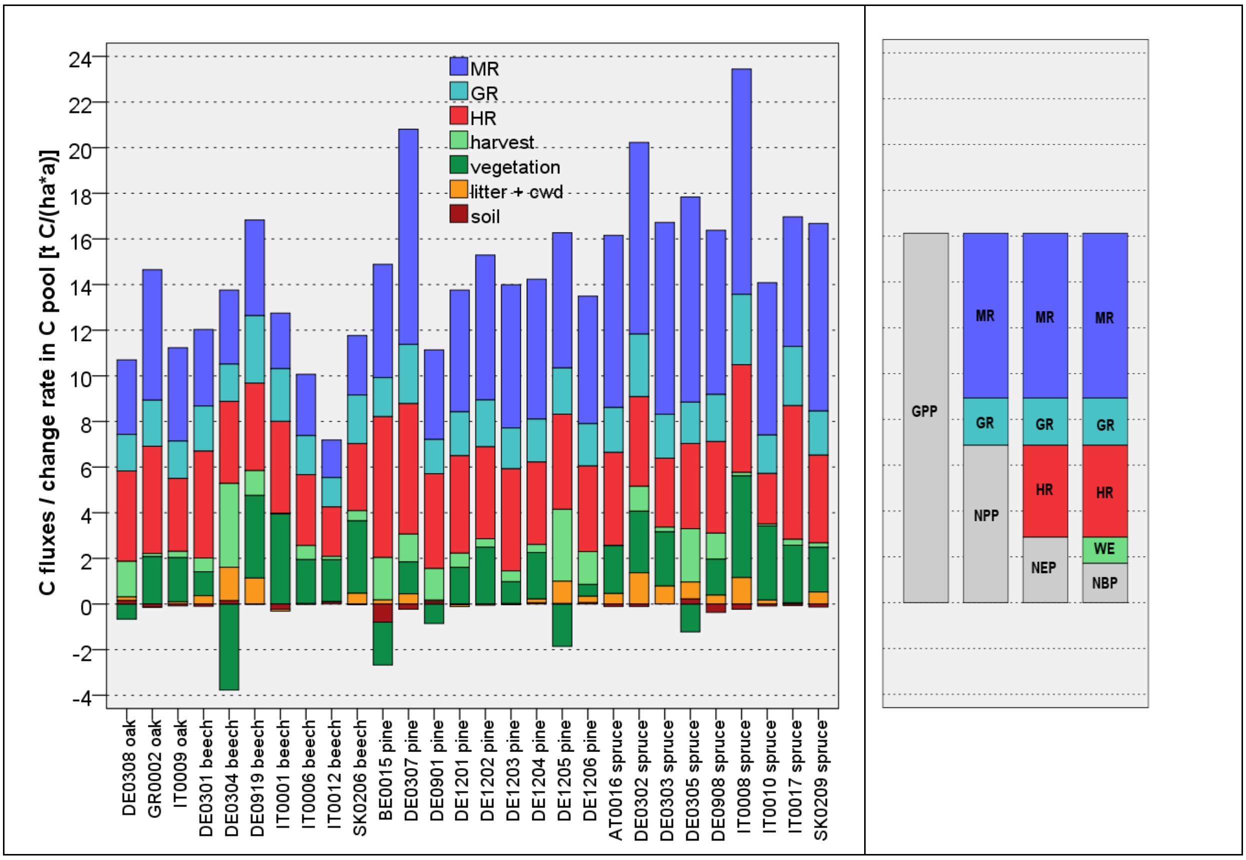


Fig. 25 Simulation results on carbon losses and change rates of carbon pools in vegetation, litter + coarse woody debris, and soil (t C ha^{-1} a^{-1}) of forest ecosystems at level II plots between 1996 and 2009 (MR=maintenance respiration, GR=growth respiration, HR=heterotrophic respiration, WE=wood export by harvest, GPP=gross primary production, NPP=net primary production, NEP=net ecosystem production, and NBP=net biome production).

Tab. 5 Simulation results on carbon losses (t C ha^{-1} a^{-1}) of forest ecosystems at level II plots between 1996 and 2009 (MR=maintenance respiration, GR=growth respiration, HR=heterotrophic respiration, RR=root respiration). Additionally, the carbon balances gross primary production (GPP), net primary production (NPP), net ecosystem production (NEP), and net biome production (NBP) are specified.

plot	**GPP**	**NPP**	**NEP**	**NBP**	**MR**	**GR**	**HR**	**RR**
AT0016	15.9	6.57	2.51	2.04	7.35	1.97	4.06	1.40
BE0015	12.4	5.71	-0.47	-2.32	4.96	1.71	6.18	1.72
DE0301	11.9	6.59	1.90	1.30	3.35	1.98	4.69	1.54
DE0302	20.3	9.13	5.20	4.11	8.40	2.74	3.93	1.58
DE0303	16.8	6.42	3.39	3.19	8.41	1.93	3.02	1.32
DE0304	10.3	5.45	1.86	-1.81	3.24	1.64	3.59	2.06
DE0305	16.8	6.04	2.30	-0.03	8.99	1.81	3.74	1.08
DE0307	20.7	8.64	2.93	1.71	9.43	2.59	5.72	2.19
DE0308	10.2	5.34	1.38	-0.18	3.27	1.60	3.96	1.38
DE0901	10.4	5.01	0.86	-0.53	3.93	1.50	4.15	1.44
DE0908	16.1	6.87	2.86	1.71	7.19	2.06	4.02	1.75
DE0919	17.0	9.85	6.02	4.93	4.19	2.96	3.83	1.43
DE1201	13.7	6.41	2.13	1.52	5.34	1.92	4.27	1.56
DE1202	15.3	6.85	2.82	2.45	6.35	2.06	4.03	1.34
DE1203	14.0	5.95	1.47	1.00	6.28	1.79	4.48	1.97
DE1204	14.3	6.28	2.66	2.31	6.13	1.88	3.61	1.50
DE1205	14.7	6.74	2.57	-0.59	5.93	2.02	4.17	1.54
DE1206	13.6	6.20	2.45	1.02	5.58	1.86	3.75	1.09
GR0002	14.5	6.74	2.04	1.90	5.71	2.02	4.70	2.41
IT0001	12.4	7.70	3.69	3.65	2.43	2.31	4.02	1.35
IT0006	10.1	5.71	2.60	1.98	2.68	1.71	3.11	1.03
IT0008	23.2	10.28	5.55	5.40	9.87	3.08	4.72	2.28
IT0009	11.2	5.46	2.26	1.99	4.09	1.64	3.20	1.73
IT0010	14.0	5.62	3.40	3.31	6.68	1.68	2.22	1.11
IT0012	7.3	4.34	2.16	2.02	1.68	1.30	2.18	0.77
IT0017	16.9	8.67	2.81	2.56	5.68	2.60	5.86	2.20
SK0206	11.8	7.08	4.14	3.69	2.61	2.12	2.94	0.93
SK0209	14.7	5.81	2.30	2.06	7.13	1.75	3.52	1.66
mean	14.3	6.69	2.71	1.80	5.60	2.01	3.99	1.55

Tab. 6 Simulation results (t C ha^{-1} a^{-1}) on stem growth (SG), wood export by harvest (WE), litterfall rates from leaf (LF_L), wood+fruit (LF_{SF}), and root (LF_R), and change rates of carbon pools in vegetation (ΔVeg), leaf + fine root litter (ΔL_{L+FR}), coarse woody debris (ΔCWD), and soil (ΔSOC) of the model calibration period using measured meteorological data.

plot	SG	WE	LF_L	LF_{SF}	LF_R	ΔVeg	ΔL_{L+FR}	ΔCWD	ΔSOC
AT0016	1.98	0.47	1.51	1.11	1.72	1.58	0.19	0.38	-0.11
BE0015	0.98	1.85	0.99	1.52	2.20	-1.72	0.09	0.10	-0.80
DE0301	1.87	0.60	1.81	1.09	1.84	1.08	0.44	-0.14	-0.07
DE0302	3.81	1.09	1.03	1.59	1.87	2.92	0.30	1.01	-0.12
DE0303	2.76	0.21	1.22	0.58	1.92	2.41	0.46	0.31	0.01
DE0304	1.50	3.68	1.46	0.86	1.49	-3.38	0.89	0.53	0.14
DE0305	2.11	2.34	1.42	0.65	1.75	-0.97	0.35	0.36	0.22
DE0307	2.85	1.22	1.57	1.01	2.63	1.53	0.08	0.33	-0.24
DE0308	1.47	1.56	1.29	1.17	1.29	-0.51	0.09	0.09	0.15
DE0901	1.20	1.38	1.05	0.65	2.04	-0.69	0.03	0.04	0.10
DE0908	2.92	1.14	1.32	0.33	1.86	1.71	0.07	0.31	-0.37
DE0919	4.83	1.09	1.90	0.87	1.93	3.77	1.07	0.10	-0.01
DE1201	2.13	0.62	1.16	0.92	1.84	1.62	0.01	-0.09	-0.02
DE1202	2.79	0.37	1.16	0.97	1.75	2.49	0.01	-0.06	0.01
DE1203	1.43	0.47	1.10	1.22	1.99	1.00	0.04	-0.02	-0.02
DE1204	2.40	0.35	1.28	0.88	1.56	2.08	0.03	0.15	0.06
DE1205	2.46	3.15	1.31	1.06	1.64	-1.51	0.29	0.62	0.01
DE1206	2.41	1.44	1.15	1.18	1.26	0.67	0.06	0.23	0.06
GR0002	2.06	0.13	2.43	0.12	1.95	2.05	0.02	-0.05	-0.12
IT0001	3.63	0.04	1.31	0.44	1.93	3.97	0.20	-0.29	-0.23
IT0006	2.68	0.62	1.20	0.27	1.28	2.00	0.07	-0.11	0.02
IT0008	4.27	0.15	2.15	1.04	2.45	4.44	0.98	0.21	-0.23
IT0009	2.13	0.28	1.60	0.12	1.33	2.00	0.15	-0.07	-0.09
IT0010	3.05	0.09	1.07	0.15	1.06	3.22	0.12	0.06	-0.09
IT0012	1.98	0.15	1.07	0.06	1.11	1.89	0.24	-0.19	0.08
IT0017	2.64	0.25	2.53	0.74	2.51	2.55	-0.06	0.14	-0.07
SK0206	3.72	0.45	1.23	0.70	1.30	3.24	0.58	-0.11	-0.03
SK0209	1.70	0.24	1.61	0.55	1.74	1.59	0.55	0.01	-0.09
mean	**2.49**	**0.91**	**1.43**	**0.78**	**1.76**	**1.47**	**0.26**	**0.14**	**-0.07**

3.2.4 Carbon balance

For most plots a positive net ecosystem production (mean NEP= 2.7 t C ha^{-1} a^{-1}) as well as a positive net biome production (mean NBP= 1.8 t C ha^{-1} a^{-1}) was calculated during the calibration period (Fig. 26). Negative NEP was computed for plot BE0015 which was induced by an unrealistically high simulated heterotrophic respiration rate of this groundwater influenced site. Six plots show negative NBP values corresponding to strong harvest actions.

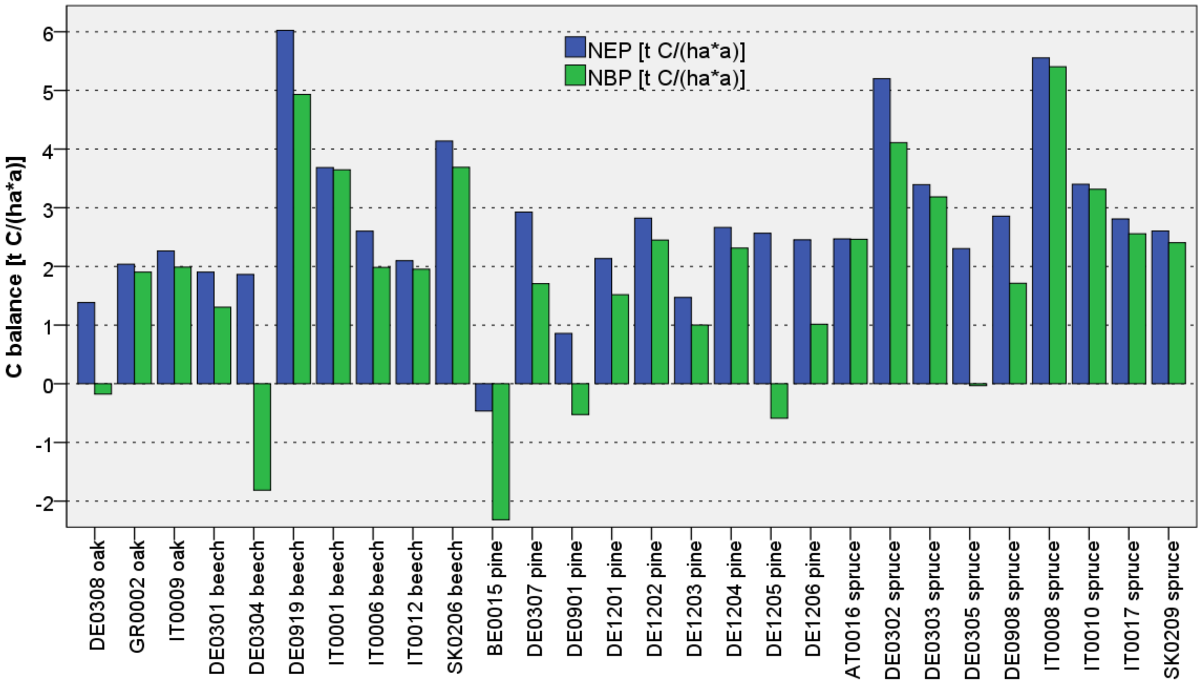


Fig. 26 Simulated carbon balances (NEP = net ecosystem production, NBP = net biome production) of investigated plots using measured climate data over 1996-2009

3.2.5 Drought stress

As described in the introduction, summer precipitation is expected to decrease in future while the temperature is expected to increase. These factors increase the probability of drought stress for plants.

Precipitation is not the only factor impacting stem growth, but the results in Fig. 27 show, that the amount of summer precipitation explains about 53 % of the annual variation of the stem growth on the investigated plots.

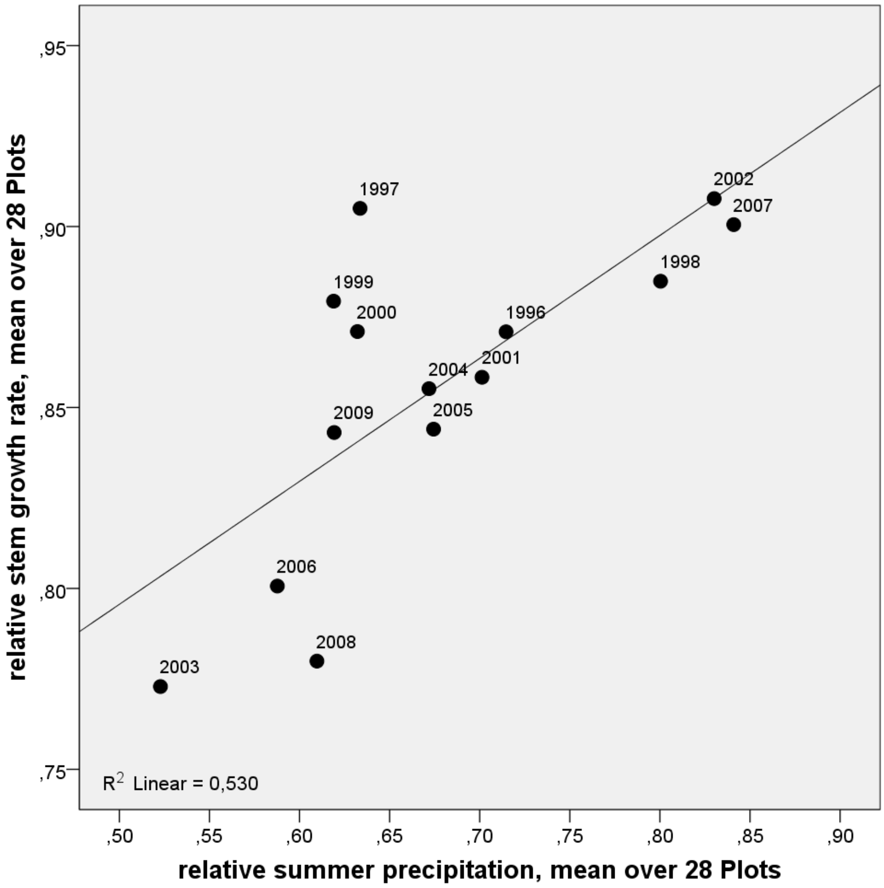


Fig. 27: Correlation between summer precipitation and simulated stem growth. For each plot, the relative summer precipitation (May-October) and relative stem growth rates were computed by dividing the annual values by the maximum annual value. The figure shows the mean of these relative values over 28 investigated plots.

3.3 Simulation results under changing climate

3.3.1 Climate change effects on phenology

One of the main factors determining the assimilation of CO_2 to biomass is the length of the vegetation period that is strongly influenced by the assumed temperature development of the climate projections.

The simulation results show an elongation of the vegetation periods by 2 to 19 (mean = 10) days (under the A1B climate during the latest period until 2100) which corresponds to 0.8 – 15.4 % of the vegetation length under current climate. This is mainly caused by an earlier leaf flushing and temperatures in spring, whereas leaf litterfall plays a minor role. For B1 the vegetation period was elongated by 1 – 13 days corresponding to 0.5 – 10.3 % of the vegetation period. Smaller effects were simulated for the period 2040-2059.

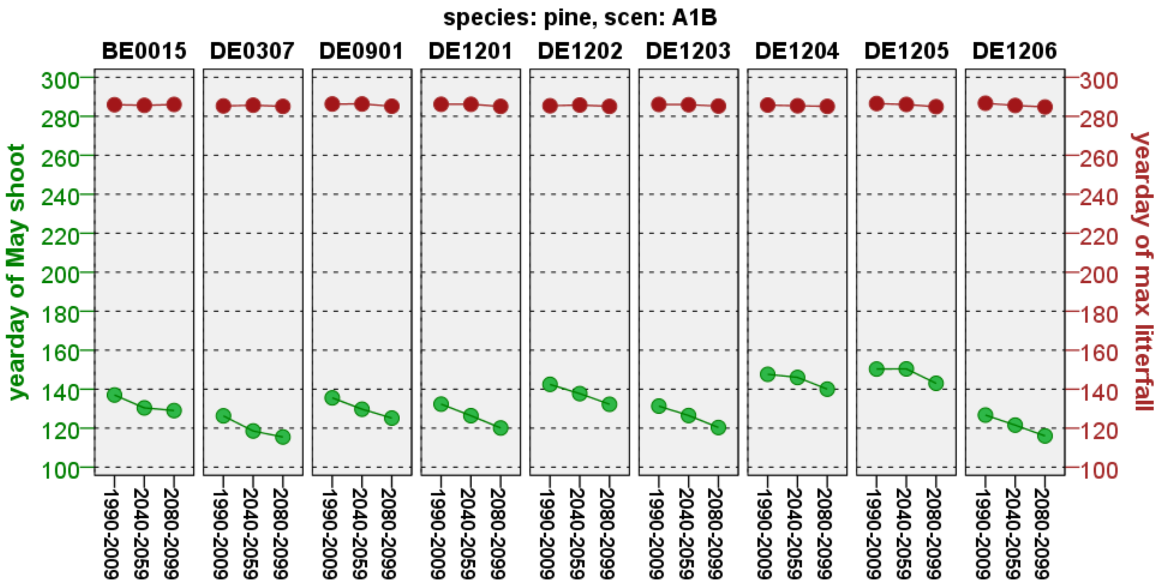


Fig. 28 Development of the simulated yearday for May shoot and maximum needle litterfall of the investigated pine forest stands in proceeding time steps of the climate scenario A1B

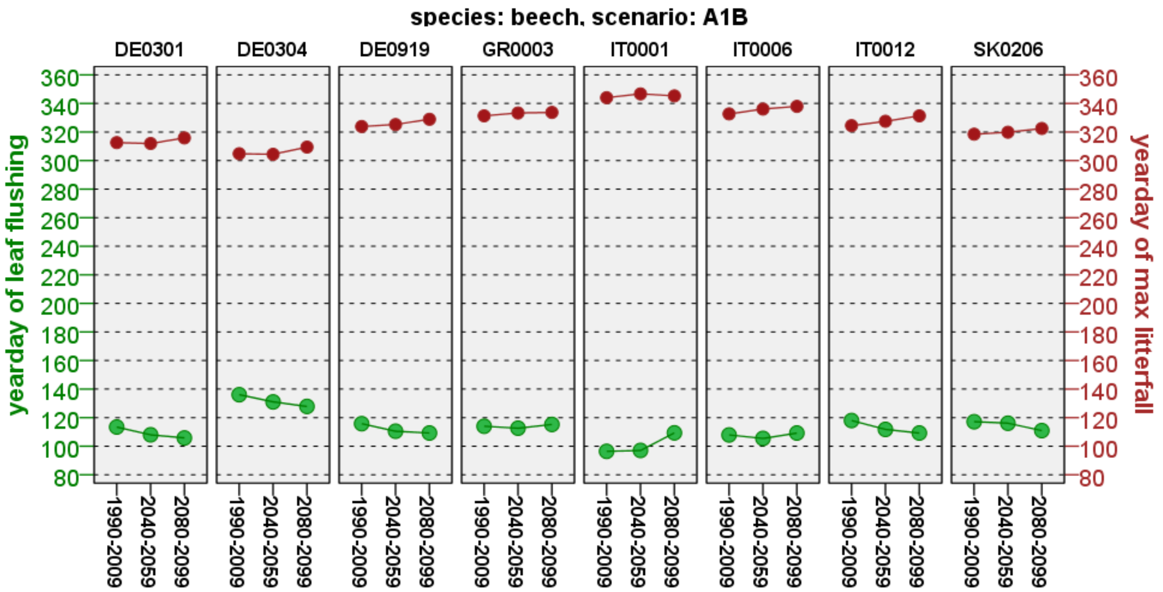


Fig. 29 Development of the simulated yearday for leaf flushing and maximum leaf litterfall of the investigated beech forest stands in proceeding time steps of the climate scenario A1B

Tab. 7 Development of the simulated leaf flushing / May shoot, leaf/needle litterfall and length of vegetation period of the investigated forest stands in proceeding time steps under the climate scenario A1B

		yearday of leaf flushing / May shoot			yearday of maximal litterfall			length of vegetation period (d)		
Species	**Plot**	**1990/ 2009**	**2040/ 2059**	**2080/ 2099**	**1990/ 2009**	**2040/ 2059**	**2080/ 2099**	**1990/ 2009**	**2040/ 2059**	**2080/ 2099**
beech	DE0301	114	108	106	312	312	316	199	204	210
beech	DE0304	136	131	128	305	304	309	169	173	181
beech	DE0919	116	111	109	324	325	329	208	215	219
beech	GR0003	114	113	115	331	334	334	217	221	219
beech	IT0001	96	97	110	344	347	345	248	249	236
beech	IT0006	108	106	109	333	336	338	224	230	228
beech	IT0012	118	112	109	324	328	331	207	216	222
beech	SK0206	117	116	111	318	320	322	201	204	211
oak	DE0308	120	111	107	319	321	323	199	209	217
oak	GR0002	98	96	99	357	359	360	259	262	261
oak	IT0009	59	64	79	352	353	351	292	289	272
pine	BE0015	137	131	129	286	286	286	149	155	157
pine	DE0307	126	119	116	285	286	285	159	167	169
pine	DE0901	136	130	125	286	286	285	150	157	160
pine	DE1201	132	126	120	286	286	285	154	160	165
pine	DE1202	142	138	132	285	286	285	143	148	153
pine	DE1203	131	127	121	286	286	285	155	160	165
pine	DE1204	148	146	140	286	286	285	138	140	145
pine	DE1205	150	150	143	287	286	285	137	136	142
pine	DE1206	127	122	116	286	286	285	160	164	169
spruce	AT0016	149	142	135	285	285	284	136	143	149
spruce	DE0302	134	128	123	286	285	285	152	158	162
spruce	DE0303	134	128	123	286	285	285	152	158	162
spruce	DE0305	137	130	126	285	286	285	148	156	159
spruce	DE0908	140	134	129	286	286	285	146	152	156
spruce	IT0008	151	144	137	286	285	286	135	142	149
spruce	IT0010	152	142	135	287	285	285	135	143	150
spruce	IT0017	163	152	143	286	285	285	123	133	142
spruce	SK0209	135	131	125	286	286	285	151	155	160
average		**128**	**124**	**121**	**302**	**303**	**303**	**174**	**179**	**182**

3.3.2 Climate change effects on water budget

As described in chapter 2.2.1.2 the precipitation within the applied climate projections increases by 76 - 107 mm a^{-1} compared to the reference scenario (C20/A1B or C20/B1 run of FutMon_CLM) depending on the time period and the emission scenario. In contrast, the summer precipitation rates for 2080-2099 decrease by 26 - 85 mm a^{-1}. This difference may influence the simulated carbon budget. On the other hand, the simulated development of leaves may impact the water budget. In order to analyse and to illustrate those interdependencies between water and carbon budget, the simulation results on the water budget have to be described here (Tab. 8).

The enhanced precipitation leads to an increased stand precipitation and a higher water outflow to seepage of similar magnitude. The canopy evaporation increases considerably, but on the other hand the soil evaporation and especially the transpiration rates are simulated to decrease under the conditions of future climate projections.

Tab. 8 Simulation results on water fluxes as average over all plots. The water fluxes of the reference period (1990-2009) and the differences of the future periods (2040-59, 2080-99) to the reference period and the percentage of these differences are shown.

		value in 1990-2009 (mm/a)	difference to 1990-2009 (mm/a)		change (%) compared to 1990-2009	
			2040-59	2080-99	2040-59	2080-99
precipitation	B1	944	106.8	87.6	11.3	9.3
	A1B	962	76.4	83.5	7.9	8.7
summer precipitation (May-Oct)	B1	551	30.6	-26.0	5.6	-4.7
	A1B	563	-1.3	-84.7	-0.2	-15.0
stand precipitation	B1	707	72.1	41.2	10.2	5.8
	A1B	720	37.5	26.1	5.2	3.6
canopy evaporation	B1	237	34.7	46.4	14.6	19.6
	A1B	242	38.8	57.4	16.0	23.7
soil evaporation	B1	66	-3.7	-7.5	-5.6	-11.4
	A1B	66	-6.5	-8.3	-9.9	-12.6
transpiration	B1	253	-9.7	0.2	-3.8	0.1
	A1B	249	-1.9	-12.2	-0.7	-4.9
water outflow	B1	384	85.3	50.3	22.2	13.1
	A1B	401	45.2	50.4	11.3	12.6

The changing climate conditions lead to increasing drought stress. This can be shown for some indices the simulation model uses for the calculation of primary production. Both, the reduced soil water availability and the increasing vapour pressure deficit of the air reduce stomatal conductance during the summer months (Fig. 30). Reduced soil water contents and higher vapour pressure deficits lead to stronger stomata closure during summer season for the time period 2080-2099. However, due to increased amounts of winter precipitation, the soil water drought stress is reduced in spring for both future time periods and scenarios. Under the B1 scenario the drought stress indices differ only little from the reference time period (1990-2009) during the time period 2040-2059.

In contrast to that the reduction of stomatal conductance due to freezing night temperatures during physiologically active periods in spring and autumn is lowered under future climate (Fig. 30).

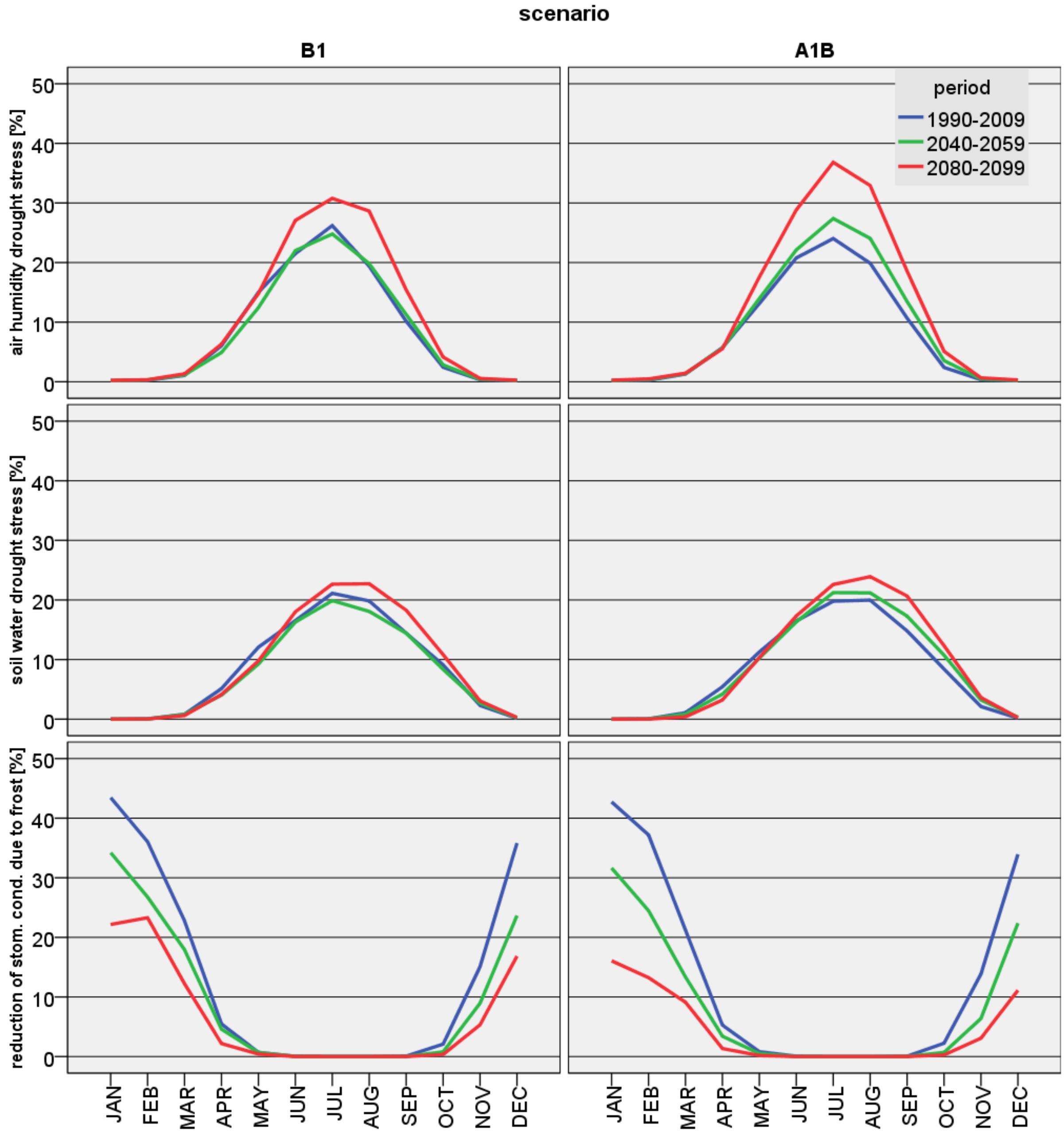


Fig. 30: Development of climate induced drought stress (% reduction of stomatal conductance) under expected future climate conditions. The stomatal conductance was simulated to be affected by air humidity (vapour pressure deficit), soil water content, and freezing night temperatures.

3.3.3 Climate change effects on carbon budget

The effects of changed climate conditions on the carbon budget are shown in a series of scattergrams (Fig. 31, Fig. 32, Fig. 33). The simulation results on the carbon budget under changing climate compared to the reference period (FutMon_CLM, 1990-2009) are presented as scattergrams, where the two emission scenarios (B1 and A1B runs of FutMon_CLM) for two time periods are denoted. Every point of the scattergram designates the result of one plot as an average over the corresponding simulation periods. The blue (2040 – 2059) and green (2080 – 2099) lines are linear regressions of these points. The points above the 1:1 line show an increase of the parameter, the points below a decrease. The results are summarized as averages over all simulated level II plots and additionally as difference and percental changes of the two future periods compared to the past in Fig. 34 and Tab. 9.

Compared to the reference period (C20/B1 or C20/A1B run of FutMon_CLM) rising gross primary productions (GPP) with changes of 1.2 to 4.8 t C ha^{-1} a^{-1} or 9 to 35 % are simulated (Fig. 34). One plot with extremely low GPP is a result of erroneous climate scenarios. The short wave radiation is lowered by 40% for both the reference period and future periods compared to measured values (see chapter 2.2.1.2).

But similar to the GPP all respiratory processes are increased, too. The proportional increase of maintenance respiration (MR) ranges between 12 and 55 % and exceeds those of the GPP. The increase of growth respiration (GR) is 7 – 22 %, the one of the heterotrophic respiration 6 – 20 %.

Carbon balances (NPP, NEP, and NBP) constituting differences of assimilatory and respiratory processes (and other carbon export processes form the ecosystem) are simulated to rise under future climate conditions. The mean NPP amounts to 6.4 t C ha^{-1} a^{-1} on average between 1990 and 2010 and rises by 0.5 to 1.4 t C ha^{-1} a^{-1} (7 – 22 %). Similar relative change rates were simulated for NEP as the difference of NPP and heterotrophic respiration (10 – 26 %). The NBP shows a very small absolute increase (0.2 – 0.6 t C ha^{-1} a^{-1}) under future climate, but the relative changes are higher (13 – 35 %).

Stem growth as part of the NPP is accelerated under changing climate, similar to the litterfall rates of leaf, wood+fruit, and roots (Tab. 9).

The mean shoot to root ratio increased slightly from 0.169 for 1990 – 2009 to 0.171 for 2040 – 2059 and to 0.172 for 2080 – 2099 under the B1 scenario. There was as well an increase under the A1B scenario, the average of which was however slightly higher (0.173 for 2080 – 2099). As the allocation pattern is triggered by constant model parameters, this has to be related to the effect of increasing temperature on the respiration rates.

Under the climate reference scenarios the mean net change rates of the carbon pools are calculated as 1.4 t C ha^{-1} a^{-1} for vegetation, 0.25 for litter, and 0.14 for coarse woody debris, whereas the soil carbon pool decreases by 0.14 t C ha^{-1} a^{-1}. Compared to the reference period these annual change rates are enhanced by 15 – 47 % for the vegetation pool. The storage change rate of litter is enhanced by 10 – 20 %, whereas the change rate of coarse woody debris is reduced by 8 – 28 %. The carbon loss from soil is accelerated under future climate condition by 13 – 64 %.

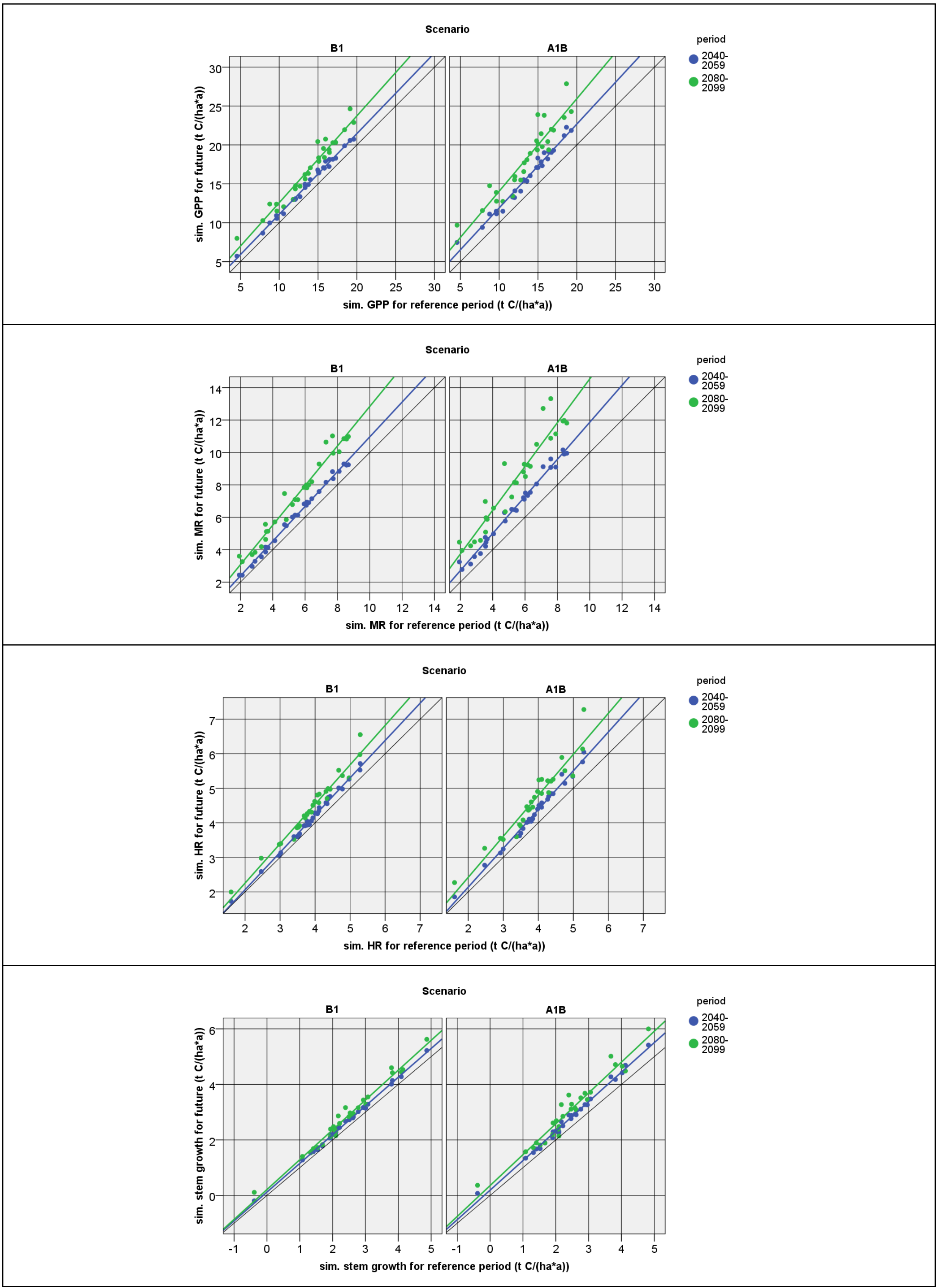


Fig. 31 Simulation results on gross primary production (GPP), maintenance respiration (MR), heterotrophic respiration (HR), and stem growth of all plots for future time periods of the climate scenarios (A1B, B1) in relation to the reference period (C20/A1B, C20/B1 run 1990-2009).

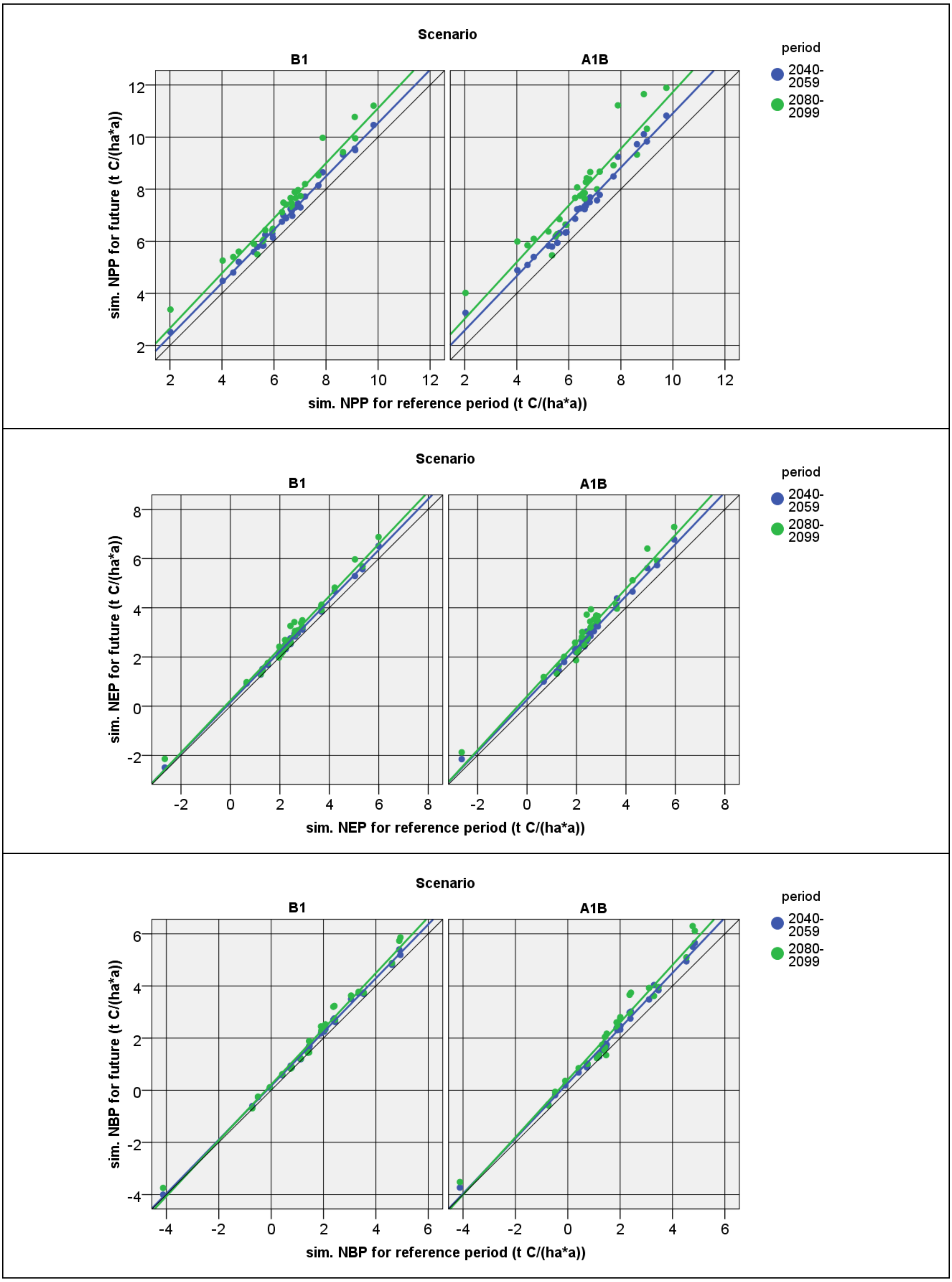


Fig. 32 Simulation results on net primary production (NPP), net ecosystem production (NEP), and net biome production (NBP) of all plots for future time periods of the climate scenarios (A1B, B1) in relation to the reference scenario of the past (C20/A1B, C20/B1 run 1990-2009).

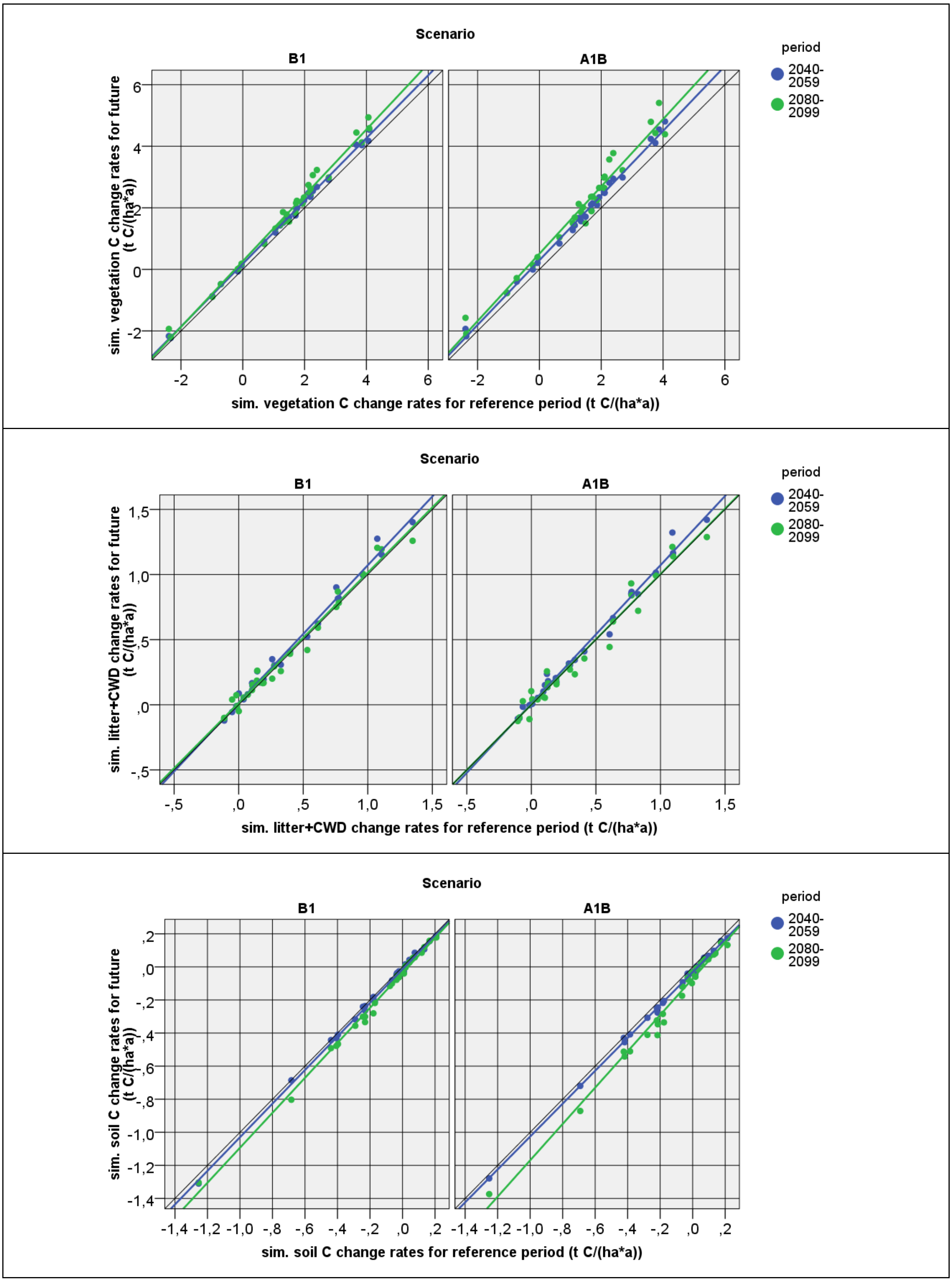


Fig. 33 Simulation results on change rates of vegetation, litter+cwd, and soil carbon of all plots for future time periods of the climate scenarios (A1B, B1) in relation to the reference scenario of the past (C20/A1B, C20/B1 run 1990-2009).

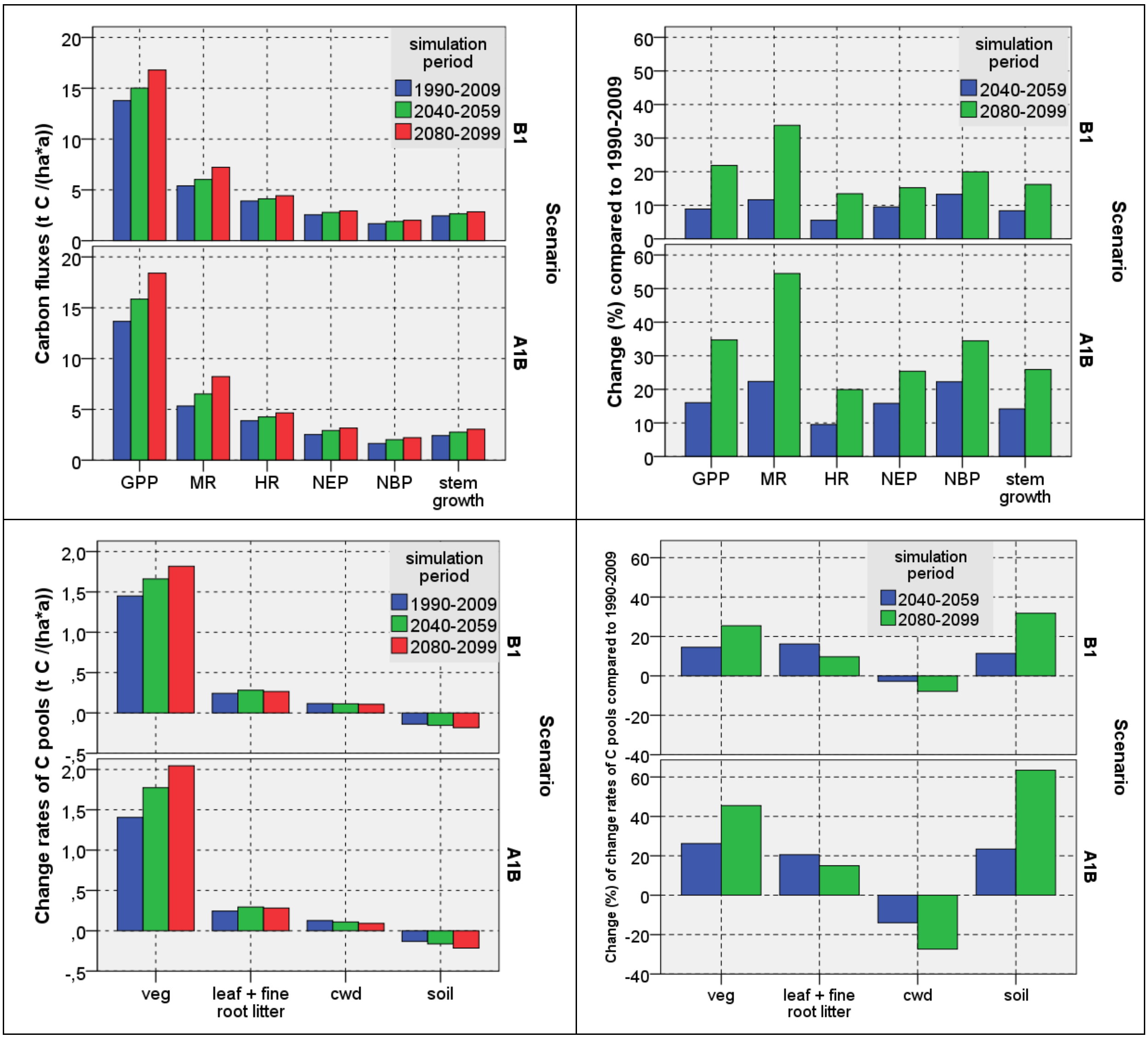


Fig. 34 Simulation results on carbon fluxes (top) and on change rates of carbon pools (bottom) as averages over all plots. The carbon fluxes (left) and the changes (%) of fluxes or of change rates of pools (right) of the periods 2040-2059 and 2080-2099 compared to the reference period (1990-2009) are shown.

Tab. 9 Simulation results on carbon fluxes and on change rates of carbon pools as average over all plots. The carbon fluxes of the reference period (1990-2009) and the absolute and relative differences of these fluxes or of change rates of pools of the periods 2040-2059 and 2080-2099 compared to the reference period (1990-2009) are shown.

		value in 1990-2009 (t C $ha^{-1}a^{-1}$)	difference to 1990-2009 (t C $ha^{-1}a^{-1}$)		change (%) compared to 1990-2009	
			2040-59	2080-99	2040-59	2080-99
gross primary production (GPP)	B1	13.71	1.23	3.02	9.0	22.0
	A1B	13.58	2.20	4.76	16.2	35.1
maintenance respiration (MR)	B1	5.35	0.63	1.83	11.8	34.2
	A1B	5.27	1.20	2.90	22.7	55.1
growth respiration (GR)	B1	1.93	0.14	0.28	7.2	14.3
	A1B	1.92	0.23	0.43	12.1	22.4
net primary production (NPP)	B1	6.43	0.46	0.92	7.2	14.3
	A1B	6.39	0.77	1.43	12.1	22.3
heterotrophic respiration (HR)	B1	3.89	0.22	0.53	5.6	13.5
	A1B	3.87	0.37	0.78	9.6	20.1
net ecosystem production (NEP)	B1	2.55	0.24	0.39	9.6	15.4
	A1B	2.52	0.40	0.65	16.0	25.8
wood export by harvest (WE)	B1	0.88	0.02	0.05	2.2	6.1
	A1B	0.88	0.03	0.07	3.6	8.3
net biome production (NBP)	B1	1.67	0.22	0.34	13.4	20.3
	A1B	1.65	0.37	0.58	22.6	35.1
stem growth	B1	2.43	0.21	0.40	8.4	16.4
	A1B	2.41	0.35	0.63	14.3	26.2
leaf litterfall	B1	1.35	0.09	0.19	6.8	14.3
	A1B	1.35	0.15	0.28	11.0	20.9
wood+fruit litterfall	B1	0.74	0.02	0.05	2.7	7.1
	A1B	0.74	0.03	0.07	4.4	9.4
root litterfall	B1	1.68	0.10	0.21	5.8	12.7
	A1B	1.68	0.16	0.30	9.5	18.2
ΔVeg	B1	1.43	0.22	0.38	15.4	26.5
	A1B	1.39	0.38	0.66	27.5	47.4
ΔL_{L+FR}	B1	0.25	0.03	0.02	12.9	9.5
	A1B	0.25	0.05	0.04	20.4	17.4
ΔCWD	B1	0.13	-0.01	-0.02	-7.8	-13.5
	A1B	0.14	-0.03	-0.04	-18.1	-28.3
ΔSOC	B1	-0.14	-0.02	-0.05	13.1	33.4
	A1B	-0.14	-0.04	-0.09	27.1	63.5

4 Discussion

In the present study the carbon budget of forest ecosystems of selected FutMon / ICP Forests level II plots was simulated with the dynamic model Biome-BGC (version ZALF) using measured data obtained by the level II program.

After a model calibration the application of climate data from CLM-climate projections with two CO_2 emission scenarios (A1B, B1) over two different time periods (2040-2059 and 2080-2099) enabled the assessment of the effects of climate change in comparison to a reference period (1990-2009).

Simulations were performed on 28 European plots of the FutMon / ICP Forests level II program. The selection of the plots was based on the availability of measured data for model initialization and calibration. Information was unconditionally needed on meteorology, initial values for stem and soil organic carbon pools, soil physical and hydrological parameters, and nitrogen deposition. Further criteria for plot selection have been the availability and quality of calibration data on forest growth and litterfall. Further information on stand precipitation, soil hydrology, transpiration, phenology, LAI, time series of SOC, soil respiration, and soil temperature was used if present.

The used data for model initialization and calibration mainly originate from the level II database of the vTI Institute for World Forestry, Hamburg. Additional data were provided by German forest institutes (LFE, NW-FVA, LWF). Soil profile descriptions were derived mainly from the BioSoil project and partly supplemented with data from the European Soil Database (ESDB). Different yield tables were used in order to derive harvest rules. Small parts of the model parameters could be derived from the level II database, else literature values were taken as basis for the calibration procedure.

Gaps in the measured meteorological data were filled by the use of NCEP/NCAR and E-OBS data. The FutMon_CLM climate projections were conducted and made available by the vTI Institute for World Forestry, Hamburg.

4.1 Assessment of simulation results

4.1.1 Model calibration

During the process of model calibration we tried to achieve the best possible fitting of simulation results to the measured data within plausible ranges of model parameters. This succeeded to different extents. There are different possible reasons if the simulated values of a process or a time series of state variable deviate from the measured ones. The input or calibration data may contain errors, or the differences may be caused by weaknesses of the model structure or the modelling approach. For this reason it seems to be important to investigate the reasons for deviations between simulated and measured values. As a result of these analyses recommendations for improvements for the data acquisition and the model structure can be drawn.

As correct simulations of hydrology and soil temperature of forest ecosystems are essential preconditions for estimating the carbon budget of forest ecosystems with dynamic simulation models, the reliability of these simulation results have to be discussed here, too.

The **soil temperature** can be simulated with rather high precision. Some weaknesses under snow during the winter time probably have no large effects on the simulated decomposition and can be neglected.

The simulation results on water budget have to be discussed in more detail. All parts of the water budget of the forest ecosystems are strongly dependent on the diurnal variation of **meteorology**, especially of precipitation. Gaps in the meteorological data had to be closed with data from more or less far-off meteorological stations or from gridded data sets. This can cause deviations between the observed and simulated soil water contents.

Stand precipitation and **canopy evaporation** can be simulated with rather good agreement to the measured values. Some deviations between simulated and measured stand precipitation and canopy evaporation data during winter time can be related to the inability of the model to represent the **storage of snow** in the canopy. The canopy evaporation is in fact not measured directly, but calculated as the difference between bulk precipitation and stand precipitation. These factors resulted in a low model performance concerning canopy evaporation.

The correlations of simulated to measured **soil moisture** values differ plotwise and often soil depth-wise. Good conformances could be achieved for many plots, especially in the upper soil layer. In case of discrepancies there are a large number of possible reasons.

As the model uses a capacity approach for simulation of the soil water budget (see chapter 2.1), the simulation results are sensitive to the **soil hydrological model parameters** (pv, fc, pwp, kf), that were measured in some cases or have been calculated using pedotransfer functions, based on bulk density, stones or gravel content, the soil texture, and organic carbon concentrations. Sometimes there is uncertainty about the unit of measured **skeleton content** (mass or volume %) and whether the **bulk density** is related to the fine soil or to the total soil. On the other hand measured values from **TDR probes** seem to be erroneous in some cases. These uncertainties result very often in large discrepancies between the soil hydrological parameters (pv, fc, pwp) and measured soil moisture from TDR probes that hinder good correlations between simulated and measured soil moisture. An alternating use of calculated soil moisture from measured **matric potential** using the pedotransfer functions or even measured water retention functions seems not to be appropriate in view of the results. In many cases the calculated soil moisture does not fit to the absolute ranges of soil moisture from other sources. But they may indicate a beginning and ending of water uptake.

Concerning the calibration of the **transpiration** it should be noted that measured data are available only for very few plots, although this would supply very valuable information on rates water uptake rates and their limits.

The **evapotranspiration of ground vegetation** has neither been measured nor simulated. On plots with a dense ground vegetation layer its soil water uptake may impact the water budget of the whole forest stand. In order to avoid errors in the soil water balance, low transpiration rates of the trees were artificially increased for compensation of ground vegetation not taken into consideration.

There is also a degree of uncertainty in the **vertical root distribution** in the soil profile and the absolute **rooting depth** that determines the amount of available water for transpiration. For instance, under conditions of scarce precipitation at sandy over loamy soils it is known, that beneath of an upper rooting system a second one in the loamy layers may exist. Such kind of vertical root distribution cannot be covered by the model.

The quality of the water budget simulations could be significantly improved if transpiration would be measured or if the reliability of the above mentioned soil parameters would be increased.

The temporal development of the **leaf area index** (LAI) strongly influences the water and carbon exchange rates of canopies and is thus one of the most important indicators for model calibration. But measured data of the LAI are scarce. Sometimes only one measured value for the stand or a maximum and a minimum LAI are available for parameterization.

LAI is adequately simulated for most plots; on some however, considerable differences occurred. Simulation results may differ from measured data, because the model computes the LAI from the simulated leaf mass via conversion with a **constant specific leaf area**, while in reality this specific leaf area changes over time. This is obvious especially for deciduous trees, where the simulated LAI increases during the growing season, whereas the observed dynamic of LAI during the vegetation period are smaller. Another reason for deviations between measured and observed data may be that crown damages due to diseases, insect attacks or wind throw were not considered by the model. During the FutMon project, in many cases the LAI was derived from optoelectrical methods. It is noticeable, that these values usually lie below the values derived during former investigations. A more reliable method is the combination of leaf litterfall rates with measurements of the specific leaf area. For coniferous trees, however, the number of needle age classes for calculation of annual needle turnover rate is still missing.

Concerning the aboveground part of the carbon turnover, the measurements are often sufficient and can be reproduced properly by the model. Although the simulations do sometimes not follow the growth rates that were computed from the five-yearly measured **wood increment**, the correlations between the plotwise means are in general very good.

Similarly, **litterfall** from **leaf** and from the remaining compartments of litterfall, i.e. wood from stem, branches and twigs, from bark, flowering and fruits are represented well by the model if averaged over the simulation period. But the annual variation cannot be displayed by the model leading to the conclusion, that not all important factors for the annual variation are considered by the model. Concerning the leaf/needle litterfall this might be related to factors like insect attacks or diseases caused by air pollution, and to storm events regarding the wood litterfall.

The measured annual variation is much higher for the **wood+fruit litterfall** than for the leaf litterfall. One possible reason for the low model performance concerning the annual variation of the wood+fruit litterfall might be found in the model structure that does not differentiate between stem, branch, and twig wood. In the compartmentalisation of the model all stem carbon is defined as tree wood carbon and becomes converted via expansion factors. For the reproduction organs, no model compartment is defined. To consider the aboveground fruit litterfall with the existing compartments, it was attributed to the wood litterfall. The reason for the high temporal variation of the measured wood+fruit litterfall is hence a high dynamic of branch litterfall induced by storm events and the occurrence of mast years that affect the variation of fruit litterfall.

A model calibration using annually or even higher resolved increment data as available from **tree-ring analysis** or **girth bands** would not be appropriate until the model is enhanced by an additional compartment for the fructification. Therefore, this kind of data was not used for the present study.

Only few data exist that deal with the belowground part of the carbon turnover. The carbon stocks of litter, humus layer, and mineral soil were recorded only once within the scope of the ICP Forests level II program, but no time series exist. Coarse woody debris as well as root and root litter are not measured at all.

Long-term monitoring of **soil carbon** stocks is available from two sites only (Solling beech and spruce, DE0304, DE0305). Taking into account the high temporal fluctuation (-13 t C ha^{-1} a^{-1} between 1979 and 1983 and +10 t C ha^{-1} a^{-1} in humus layer + mineral soil down to 50 cm, respectively) the results seem to be not very plausible as they cannot be explained by the carbon turnover processes in the soil. In this case the spatial heterogeneity of carbon concentration, density and stone content of the soil is too high to prove the small stock changes statistically with a reasonable amount of samples (Lloyd and McKee 1983, Klinck et al. 2008).

Additionally there are few data on carbon turnover processes in the soil. Neither the rates of increment of roots nor those of decomposition are analysed. Measurements on **soil respiration**, partly differentiating the heterotrophic and root respiration using trenching technique were carried out at 15 German level II plots. The seasonal dynamic of both sub-processes of soil respiration can be displayed by the model. But during the model calibration procedure it was not possible to receive good agreements to the measured fractions of heterotrophic and root respiration with realistic model parameters. The mean simulated vs. measured soil respiration over all 15 plots do not correlate at all (see chapter 3.1.4.4). There are many possible reasons for these deviations. Wrong initial values of soil organic carbon, coarse woody debris, and leaf litter are examples for data based causes. Other reasons could be incorrect model assumptions like parameters for allocation of assimilates to roots and root turnover fractions that determine the content of living roots and root litter in soil and the root turnover rates. Impacts of erroneous hydrological soil parameters may be another reasons, if a wrong pore volume inhibits or accelerates the aeration and thus the decomposition. Finally, the root trenching technique for separation of root and heterotrophic respiration may produce some artefacts (Hanson et al. 2000, Kuzyakov and Larionova 2005, Froitzheim 2008, Díaz-Pinés et al. 2010, Bond-Lamberty et al. 2011). Thus, these measurements are supposed to be an uncertain database for model calibration aiming on separated consideration of root and heterotrophic respiration.

4.1.2 Carbon budget under current climate conditions

4.1.2.1 Carbon stocks

The simulated aboveground biomass carbon stocks, coarse woody debris and soil carbon exceed the values from literature, while coarse and fine root carbon stocks are in the range of observed values (Tab. 10). The aboveground biomass C of considered German studies are higher than the values from European studies. The simulated aboveground biomass C value even exceeds the German values that may be explained by an over-representation of older forests in the plot selection compared to the other studies and the fact, that the selected plots are not representative for the whole area of Germany or Europe.

The high value of the simulated CWD C can be further explained by different definitions of this pool. While the German forest inventory only considers wood with a diameter thicker than 10 cm, the so called CWD C pool of the Biome-BGC additionally includes other dead wood fractions from branches, twigs, bark and coarse roots. At the moment it cannot be assessed, whether the slightly higher simulated CWD C values represent a realistic relation of the different definitions or whether the turnover rates of the wood or the degradation rates of the CWD have to be adjusted as proposed by (Rock et al. 2008).

Concerning the soil C, it has to be considered that partly different soil depths were used for the estimation of soil carbon stocks.

The belowground part of total biomass carbon was computed to an average of 13 % by Biome-BGC. That is considerably lower than what the analysis of a global carbon flux database (24 % for deciduous and 19 % for evergreen temperate humid biomes (Luyssaert et al. 2007)) and the German greenhouse gas inventory (Oehmichen et al. 2011) shows. These deviation may be caused by differing average stand ages of the data sources.

Tab. 10 Comparison of simulation results of the present study on carbon stocks (t C ha^{-1}) in 2009 with values found in literature

source	aboveground biomass	coarse root	fine root	CDW	soil
this study	**129**	**17.6**	**1.8**	**12.6**	**152**
EU1	54				90
EU2	36^{e1}, 51^{e2}, 50^{e3}	9.1^{e1}, 13.3^{e2}, 12.9^{e3}			
EU3	50.5				47
EU4	122^{c}, 91^{d}	22^{c}, 21^{d}			
EU5	149^{c}, 109^{d}	46^{c}, 26^{d}			
DE1	92	22		3.3	88
DE2	100, 57^{p}, 108^{s}, 145^{b}, 93^{o}	21, 13^{p}, 22^{s}, 27^{b}, 23^{o}	1.6^{p}, 1.2^{s}, 2.0^{b}, 2.5^{o}		
DE3			(0.5–1.1)^{p}, (1.1–2.7)^{b}, 1.4^{o}		
DE4					117
DE5					77
DE6	82, 61^{p}, 75^{s}, 131^{b}, 90^{o}			6.3, 8.9^{s}	97
DE7	108				

EU1) year 1999*, period 1981-1999 for NBP*; carbon bookkeeping model based on European forest inventories (Nabuurs et al. 2003a)*, mineral soil only*
EU2) combined data from national forest inventories for 2010 (San-Miguel-Ayanz et al. 2010)
EU3) EFISCEN application for European forests (Karjalainen et al. 2003) *, tree stocks in 1995, soil stocks in 1990*
EU4) literature analysis (Jackson et al. 1996); carbon stocks from biomass assuming constant C concentration of 50%
EU5) averages and/or ranges (25% - 75% limits) of values from global database (Luyssaert et al. 2007) for temperate forests
EU6) forests of EU27 countries in the 1990s simulated with ORCHIDEE-FM (Bellassen et al. 2011)
DE1) German greenhouse gas inventory (Oehmichen et al. 2011); soil C values for organic layer + mineral soil (0-30 cm)
DE2) literature analysis on German long-term monitoring forest sites (Jacobsen et al. 2003); carbon stocks from biomass assuming constant C concentration of 50%
DE3) north-eastern lowlands of Germany (Hornschuch et al. 2008); soil C values from 0 to 40 cm
DE4) German soil survey (BZE I) (Wolff and Riek 1996); soil C values for organic layer + mineral soil (0-90 cm)
DE5) 117 plots in Brandenburg, Germany (Konopatzky 2009); soil C values for organic layer + mineral soil (0-160 cm)
DE6) forests in Thuringia, Germany in 1993 (Wirth et al. 2004); above- and belowground CWDC, measurements supplemented by belowground fraction; SOC values from 0 to 60 cm
DE7) forests in Thuringia, Germany simulated with Biome-BGC (Vetter et al. 2005)
Species: (p) pine, (s) spruce, (b) beech, (o) oak; forest type: (c) coniferous, (d) deciduous forests; regions: (e1) Europe, (e2) Europe without Russian Federation, (e3) EU27 countries; (s) simulated under steady-state conditions

4.1.2.2 Carbon fluxes and balances

The simulated carbon fluxes GPP and the NPP with its fractions foliar, wood, and root growth as well as the rates for autotrophic and heterotrophic respiration are in the range of the considered literature values (Tab. 11). The lower NPP of pan-European area-representative estimations compared to our simulation results can be explained by the fact, that in their calculations forests with less productivity due to climatic limitations were included.

At the level II plots usually only the carbon fluxes litterfall and tree growth are measured. Application of a dynamic model can add estimations of not measured carbon fluxes. Measured values are the basis for the calibration. Hence, the close correlation of the plotwise means of simulated versus measured values during the calibration period enhances the reliability of the simulation results on the aboveground carbon balance. In contrast to stem growth and litterfall, successful model calibration of the soil respiration was not possible. On average, the same magnitude was computed, but the plotwise means did not correlate at all. Possible reasons can be seen in a mismatch of measured SOC used as initial values and the simulated steady-state SOC. In this context, alternative methods for model initialisation and calibration have to be tested. This will be discussed in in more detail in chapter 4.2.2. Despite this, the fractions of the soil respiration (HR + belowground part of MR and GR) are in the range of comparable values.

Tab. 11 Comparison of simulation results of the present study on carbon fluxes (t C $ha^{-1}a^{-1}$) in 1996-2009 with literature values; abbreviations see Tab. 10

	GPP	NPP	foliar growth	wood growth	root growth	autotrophic respiration	heterotrophic respiration
this study	14.3 (7.3 – 23.2)	6.7 (4.3-10.3)	1.5 (1.0 – 2.6)	3.3 (1.9 – 5.7)	2.0 (1.2 – 3.1)	7.6 (3.0 – 13.0)	4.0 (2.2 – 6.2)
EU1		4.8					
EU3		3.2					1.9
EU5	17.6[e] (13.9-21.3)[e] 13.8[d] (12.8-15.9)[d]	7.8[e] (5.7-9.2)[e] 7.4[d] (5.4-8.7)[d]	1.6[e] (1.2-2.3)[e] 2.4[d] (1.6-3.0)[d]	2.8[e] (2.0-4.2)[e] 3.3[d] (2.0-4.2)[d]	2.4[e] (1.7-2.8)[e] 2.1[d] (1.0-2.3)[d]	9.5[e] (8.0-15.2)[e] 6.7[d] (4.7-8.9)[d]	4.2[e] (3.0-5.9)[e] 3.9[d] (2.7-5.2)[d]
EU6	13.5	6.0				6.5	4.2
DE7	18.5	7.3				11.2	5.9

In order to answer the key question if the forest ecosystems react as carbon sources or sinks, the temporal scale has to be taken into account. NPP is regarded as short-term, NEP as medium-term, and NBP as long-term carbon sink (Grace 2005). In order to evaluate the simulation results for carbon fluxes and balances, these are compared to literature values (Tab. 12).

Tab. 12 Comparison of simulation results of the present study on carbon balances (t C $ha^{-1}a^{-1}$) in 1996-2009 with literature values; abbreviations see Tab. 10

	NEP	NBP	ΔVeg	ΔL_{L+FR}	ΔCWD	ΔSOC
this study	2.7 -0.5 - +6.0	1.8 -2.3 - +5.4	1.47 -3.38 - +4.44	0.26 -0.06 - +1.07	0.14 -0.29 - +1.01	-0.07 -0.8 - +0.22
EU1		0.84				
EU3	1.3	0.7				
EU5	4.0[e] (2.0-5.1)[e] 3.1[d] (2.2-5.3)[d]					
EU6	1.8	0.7				
DE1			0.44		0.09	0.5
DE5						0.25
DE7	1.4	1.0	1.51	0.01		-0.01

While our simulated carbon balance NEP is still in the range of comparable values, the NBP is exceeds the considered literature values. With simulation periods of 11 to 34 years, the simulated carbon fluxes do not cover a whole rotation period and are therefore only valid for the considered time period. Especially wood harvest that mainly takes place at the end of the rotation period is computed considerably below the literature values that refer to the whole rotation period. This explains why the NBP obtained from the present study is significantly higher compared to a NBP that is representative for larger areas.

The NBP reflects the change of carbon pools in vegetation, litter, CWD, and soil. This balance cannot be verified with data from the level II plots, because no time series for these carbon pools exist.

Similar to NBP, the change rates of the vegetation, litter, and CWD carbon pools were higher than comparable values of a regional application of Biome-BGC (Vetter et al., 2005) and the German greenhouse gas inventory (Oehmichen et al. 2011). Only the simulated change rate of soil carbon is smaller than the considered literature values. The high value of 0.5 t C ha^{-1} a^{-1} (Oehmichen et al. 2011) was reduced to 0.3 t after a re-evaluation of the dataset (Wellbrock et al. 2011).

4.1.3 Carbon budgets under changing climate conditions

The simulation results presented here show that for the 28 selected level II plots the changed climate conditions lead to an accelerated carbon turnover in the whole forest ecosystem. Primary production as well as autotrophic and heterotrophic respiration are simulated to increase. The carbon balances NPP, NEP, and NBP increase, even though autotrophic respiration shows higher relative increase than the primary production. A changed climate with higher temperatures, precipitation rates, and CO_2 concentrations lead to an increasing carbon sink function of the ecosystems.

The results on the enhanced wood increment under climate change conditions are in accordance with analyses of growth trends of the past (Spiecker et al. 1996, Boisvenue and Running 2006) and simulation studies for future development (Lasch et al. 2002). An application of the simulation model EFISCEN in combination with the model LPJ also resulted in an increasing stem growth of 10 – 20 % for Brandenburg, Germany with the HadCM3 climate scenarios A1 and A2 and of 0 – 10 % with B1 and B2 for the time period 2071 – 2100 compared to the current climate (Eggers et al. 2008).

For the calibration period the simulated stem growth was sensitive to changes in summer precipitation (Fig. 27). Plants react to drought by closing their stomata (Irvine et al. 1998, Schulze 2006). This reduces water loss via transpiration and can reduce photosynthesis because the leaf conductance for CO_2 decreases at the same time. Despite the fact that the simulation results predict an increase of summer drought stress for the future (Fig. 30), the stem growth rate, NEP, and NBP were increasing (Fig. 34). The summer drought effect on future growth development is not visible because it is over-compensated by the fertilizing effect of CO_2 (Ceulemans and Mousseau 1994, Curtis 1996, Jarvis 1999, Ainsworth and Long 2005, Körner 2006). With higher atmospheric concentrations the demand for CO_2 during photosynthesis can be fulfilled with lower stomatal conductance. This may lower transpiration rates and increase water use efficiency (Eamus 1991, Leuzinger and Körner 2007). Additionally, during spring and autumn reduction of stomatal conductance is simulated to be weakened under future climate conditions due to fewer frost events (Delucia 1987). Taking as well into account the improved water supply in spring, this leads to an overall enhanced annual GPP.

The length of the vegetation period also influences annual stem growth rates. Under the predicted future climate conditions higher air temperatures are assumed to lead to an increase of the photosynthetic rate (Saxe et al. 2001, Hyvönen et al. 2007) and an elongation of the vegetation period (Rötzer et al. 2004, Menzel et al. 2006). Similarly, our simulation results predict an elongation of the vegetation period under future climate conditions (Tab. 7).

According to a reconstruction of the development of carbon sinks between 1950 and 1999 (Bellassen et al. 2011), the increase of the carbon sink function could mainly be attributed to the fertilizing effect of CO_2 (61 %), and to a minor extent to climate change (26) and changes in forest age structure (13 %).

In contrast to the mentioned studies, simulation studies on pine stands in the federal state of Brandenburg, Germany predict a reduced productivity under climate change (Lasch and Suckow 2007). From studies along climate gradients (north – south, maritime – continental) different growth reactions are expected depending on the climate zone. While, the growth limiting effect of low temperature will be reduced under future climate in the boreal zone, an increase of the growth limiting drought effect is expected for the Mediterranean zone (Kellomäki et al. 2005, de Vries et al. 2007). Both effects are documented in our investigation, even if no regional differentiation was carried out.

Increasing forest growth under future climate results in higher vegetation carbon pools. But despite higher inputs into the litter+cwd and soil carbon pools the simulation results show an accelerated decomposition under future climate that seems to over-compensate the growing litter input, resulting in slightly lower SOC stocks on the investigated sites.

The accelerated heterotrophic respiration can be explained by two reasons. First of all, as a consequence of higher primary production more substrate becomes available for respiration from leaf, wood, and root litterfall (Hyvönen et al. 2007). These substrates then undergo a stronger heterotrophic respiration because of increased temperature, unless strong changes in the soil water content may inhibit the respiration due to dry conditions or stagnant moisture. As a conclusion, the relation between input fluxes into litter, CWD, and soil carbon pools on one hand and HR on the other hand leads to slightly decreasing stock change rates of the sum of these three compartments. The increased soil carbon decomposition constitutes the risk for additional destabilization of forest ecosystems, if due to external disturbances an accelerated SOC-degradation takes place.

The development of precipitation as part of the climate scenarios often determines the simulation result on forest growth. While the precipitation within the STAR scenarios (Orlowsky 2007) is decreasing, resulting in a simulated reduction of primary production (Lasch and Suckow 2007), in our investigation the FutMon_CLM scenarios predict increasing precipitation.

4.2 Reliability of simulation results

A comparison of several simulation studies on the future development of carbon stocks in European forests under climate change conditions led to widely differing results (Nabuurs et al. 2007). The simulation results and their reliability are determined by a large number of factors that can be classified into 1) model assumptions,

2) approaches for model initialisation and calibration,

3) the quality of model input or calibration data.

In case of the application of climate scenarios

4) consequences of the used simulation setup and

5) the quality of the selected climate projections

have to be considered.

4.2.1 Limits of model assumptions

The model does not consider carbon pools of flowers and fruits. In order to account for the associated carbon fluxes of **flowering and fructification** they were subsumed under wood turnover that had to be increased. Consequently, the temporal dynamic of the competing carbon sinks stem increment and fructification (Mund et al. 2010) cannot be displayed adequately.

Possible carbon losses caused by **disturbances** like wind throw, forest fire, insect attacks, or by leaf damaging atmospheric pollutants are not considered by the model. For this reason the simulated carbon balance rather represents a potential carbon sequestration. On the other hand parts of these carbon losses are compensated as they are included in the underlying calibration data.

Vertical relocation of soil organic carbon for example due to **bioturbation or leaching** of dissolved organic carbon is not considered by the simulation model. This may lead to an unrealistic accumulation or depletion of SOC in deeper soil layers.

The turnover of **ground vegetation biomass** as possible pathways of organic matter into the litter layer is neglected by the model.

The NBP equals the carbon balance of the ecosystem under consideration of the **wood export by harvest**. For the balance, the exported wood is regarded to be directly decomposed. For a consideration of the lifetime and recycling of wood products (Karjalainen et al. 2003) an extension of the model is planned.

The **specific leaf area** (SLA) is seasonally variable, but is treated as a constant by the model. This results in an overestimation of the seasonal dynamic of leaf area index. In reality the newly grown leaves are thin and become thicker by an increase of mesophyll during the vegetation period, keeping the leaf area constant.

4.2.2 Approaches for model initialization and calibration

The **experience of the model user** plays an important role as there are different approaches for the calibration procedure. Also, the assessment of deviations between measured data and simulation results does not follow objective criteria. Possible parameter optimization techniques like Gauss-Levenberg-Marquardt approach, Kalman filter, Monte Carlo, or Bayesian analysis (Waller et al. 2003, van Oijen et al. 2005, Hidy et al. 2006, Trudinger et al. 2007, Trusilova et al. 2009) could not be applied in this investigation.

In this investigation, **measured data were used as initial values** for soil carbon and estimated data for litter and CWD carbon pools. During the simulation run these pools tend to approach a steady-state which is a function of the model structure under the environmental conditions and the model parameters used. Because the turnover constants for the pools differ, the steady-state values of these carbon pools were achieved after a few years for litter, after some decades for CWD, but only after thousands of years for soil carbon. In order to lower at least the short time effects of the diverging carbon pools described above, a ten years lasting pre-simulation period was prepended to the calibration period. The calculated heterotrophic respiration and finally the carbon balances NEP and NBP are a function of the difference between the steady-state and the measured initial values for soil carbon pools. If the steady-state value exceeds the initial value of SOC, a relatively low heterotrophic respiration will lead to an accumulation of SOC. Contrary a steady-state below the initial value of SOC causes a decomposition that exceeds the input rates carbon into the soil.

An alternative approach is to use a so called **spin-up simulation** in order to estimate steady-state initial values for the calibration period (Thornton and Rosenbloom 2005, Pietsch and Hasenauer 2006). This approach has been used for application of Biome-BGC for forests of Thuringia, Germany, taking into account additional effects of land use changes (Vetter et al. 2005). Under the influence of historical forms of forest utilisation like clearing, litter raking and forest pasture during the Middle Ages (Glatzel 1991, Verheyen et al. 1999) as well as under the changing environmental conditions forest ecosystems normally deviate from steady-state conditions. As a consequence of taking steady-state SOC as initial values, a NEP of zero would be simulated, unless environmental conditions were changed. It cannot be fully excluded that this approach leads to unrealistic initial values for SOC that differ strongly from the measured ones. Otherwise it is also possible that parts of the model assumptions or the model parameterisation or even other input data are erroneous.

The **model initial values**, especially the soil and CWD carbon pools, may have strong effects on the simulated primary production (see chapter 4.2.1). This is caused by the model concept that assumes constant C:N ratios for all biomass and soil compartments. The carbon turnover is limited by meteorological conditions, CO_2 concentration, and available N and influences the changes of the carbon pools. The nitrogen pools of these compartments change according to the carbon pools because of their fixed C:N ratios and hence mobilize or immobilize mineral N in soil. Concerning the effect of high or low initial values two factors are crucial: the C:N ratio of the compartment on one hand and the size of carbon pool of these compartment relative to its size under model-steady-state conditions of the ecosystem. That means that e.g. a high input of coarse woody debris from harvest actions with a wide C:N ratio (C:N ratios ≈ 400 – 900) can reduce the amount of available mineral N pool and can hence cause a growth reduction (Pietsch and Hasenauer 2006). Conversely, high start values of soil organic carbon with a close C:N ratio can cause high releases of mineral N if the equilibrium of this carbon pool is lower, leading to high soil respiration rates and to a fertilization effect, if the ecosystem is N limited.

In this investigation a **plotwise model calibration** was carried out. This may enhance the model reliability compared to other studies, where tree species specific sets of model parameters were applied over whole of Europe.

4.2.3 Quality of input data for model calibration

In the following sections the quality of data of the level II database in context of application of biogeochemical simulation models is evaluated.

The **meteorological** data used as driving forces are not always originating from open field measurements close to the forest stands. For gap filling, data had to be used that originated from stations far away from the level II stands (see chapter 2.2.1.1). As a result larger deviations between measured and simulated values may occur, especially for stand precipitation and soil moisture, but also for soil temperature.

The data of **soil density** and **stone content** are partly very uncertain; soil texture for some plots was only available in classes, if soil data were available only from the SOM form of the level II database. If soil hydrological model parameters are derived from such uncertain soil parameters by use of pedotransfer functions this might result in errors for the simulated water balance. The soil hydraulic parameters (pv, fc) are also the basis for calculation of oxygen availability in soils, that may have an effect on the decomposition of soil organic matter and hence possibly triggers the availability of mineral nitrogen for plant growth.

In the present study, initial values for the **soil organic carbon** were derived from measured values. But because of the great spatial variability of measured basic parameters (organic carbon concentration, bulk density of soil, stone content) these initial values are very uncertain. Reliable data on initial **coarse woody debris** were even mostly missing and had to be estimated. In order to show the effect of uncertain initial model values sensitivity analyses were conducted for two plots (DE0302, DE1201) exemplarily. For that, the derived initial values were altered by ± 30% and the effects on the simulation results were analysed (Fig. 35). While varying values of litter carbon has negligible effects, increasing initial values of coarse woody debris lead to slightly decreasing primary production. In contrast, rising soil carbon initial values lead to strong increases in ecosystems carbon fluxes. A variation of 30% results in 10 – 30% variation of the simulated carbon flux rates. The relative effect is largest for the carbon balances NEP and NBP. Depending on the initial value, even the sign of the balance can change. For discussion of the reasons for these strong effects and its relevance in relation to the model initialization the reader is referred to chapter 4.2.2.

Uncertainties in **nitrogen deposition** can limit the reliability of the results. For the average of a larger number of selected level II plots, each additional kg of N input resulted in an increase in stem growth of about 1% (de Vries et al. 2009). In this study a uncertainty analysis for four plots showed large differences in the effects of changed N deposition depending on the plot. In the present study, the annual N deposition rates were computed using two different methods. While for the German plots total N deposition was calculated with the canopy balance method, for the other plots it was computed with a simpler approach summing up the N fluxes in stand precipitation. A comparison showed that N fluxes derived with the latter methods are about 3 – 35% (mean: 21 %) lower than the fluxes based on the canopy balance method. The effects of varying nitrogen deposition on carbon fluxes and indicators of carbon balance are shown in Fig. 37.

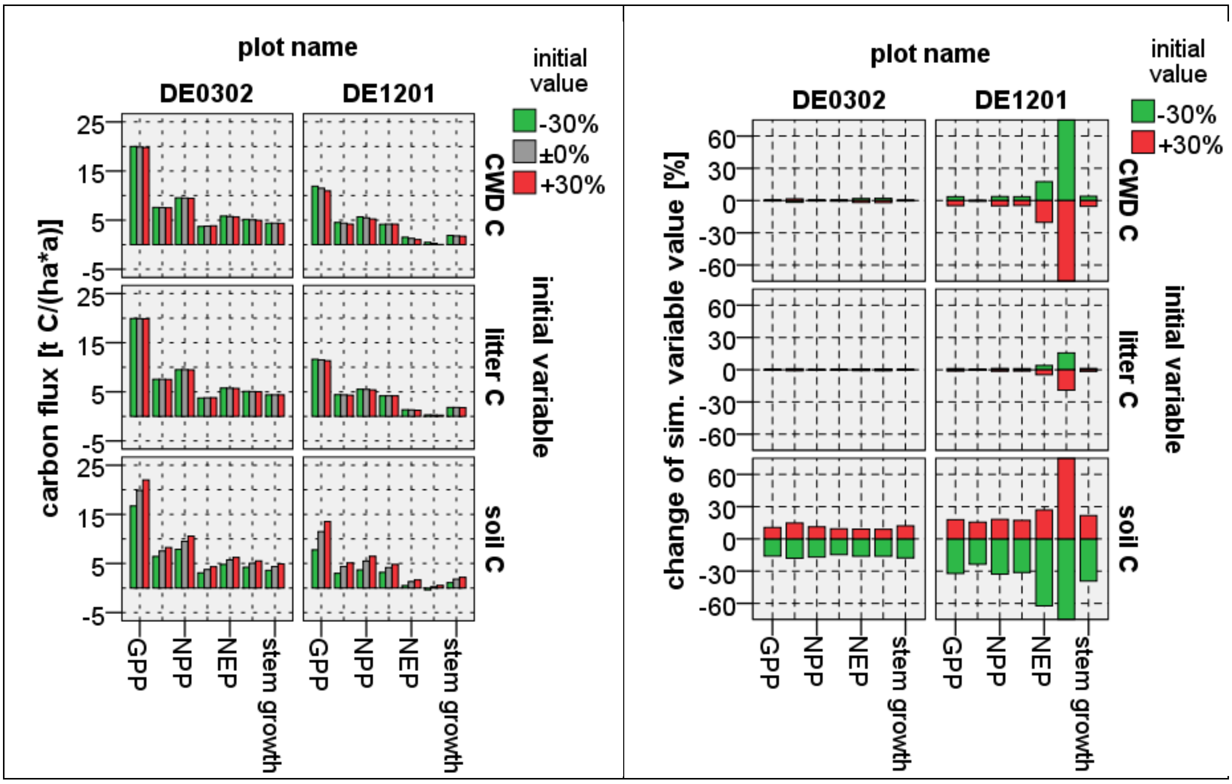


Fig. 35 Effects of varying initial soil, litter, and coarse woody debris carbon (± 30%) on carbon fluxes and indicators of carbon balance of two plots (DE0302, DE1201), expressed as influence on the absolute values (left) or percentages (right) of carbon fluxes.

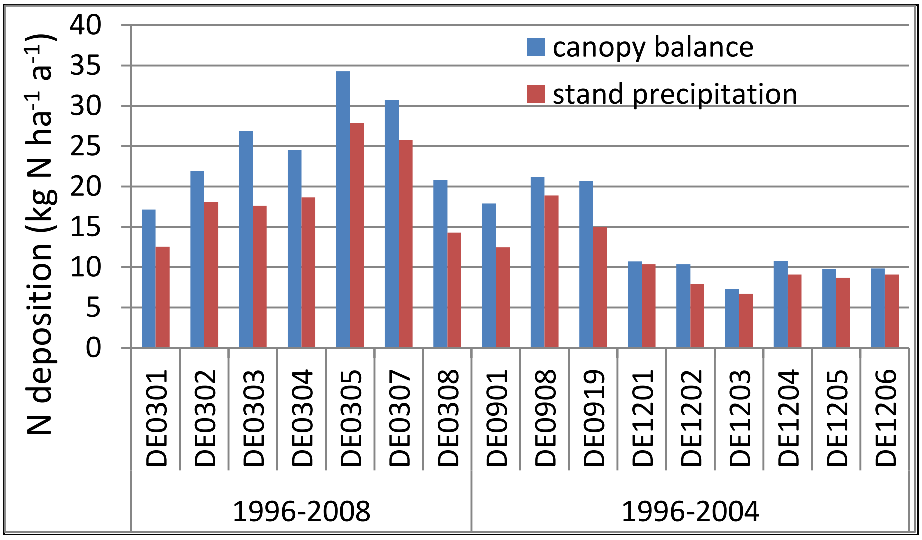


Fig. 36 Nitrogen deposition to forest stands of the investigated German level II plots as calculated using the canopy balance approach compared to the sum of mineral N fluxes in stand precipitation

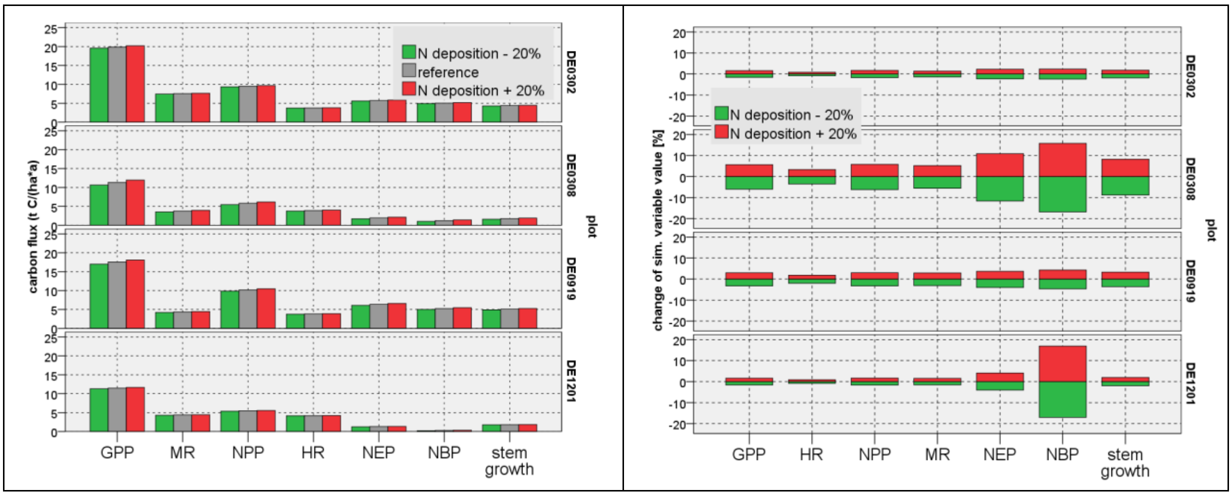


Fig. 37 Effects of varying nitrogen deposition (± 20%) on carbon fluxes and indicators of carbon balance of four plots expressed as influence on the absolute values (left) or percentages (right) of carbon fluxes.

Concerning the use of forest growth data the database was only insufficiently filled with data from 2009 as data submission was partly still on-going. In addition a number of problems occurred during the analysis of the growth rates that were derived from stock data and complicated the analysis. For individual plots and time periods negative or very low growth rates were computed that can be assigned to missing entries for the removed stem volume or to contradicting information on the survey year. For individual countries the stem volumes seemed to be related to varying areas for different survey years which made the analysis completely impossible. For these reasons aggregated data produced by a parallel study of the Expert Panel on Forest Growth was included, which was already based on an improved version of the same data (see chapter 2.2.2.1).

Concerning the litterfall data it is not clear if the guideline for the fractionation of the litterfall from the database was in fact considered by all National Focal Centres.

Concerning the interpretation of the measured LAI values it was striking, that the values strongly differed depending on the method and origin of the data. It is well known that the method for determining LAI strongly influences the results. The standardisation of measurement protocols based on the FutMon experiences is still on-going.

In general, it is a common problem, that some countries supply data in wrong units. Not all of these cases were unambiguous and allowed the transformation of wrong into correct units. In some cases data were not used since the link to metadata was missing (e.g. plot number, location of open field or forest stand, sensor type, depth or height of probe, date).

4.2.4 Quality of climate projections

Between measured meteorological data and the reference scenario (C20 run) of the FutMon_CLM data of the identical time period partly considerable systematic deviations exist (Fig. 4, Tab. A1). Plotwise deviations for the precipitation and relative humidity as well as systematic deviations concerning the global radiation and the frequency distribution of the precipitation events may have considerable effects on the simulated water budget, the photosynthesis, and the decomposition.

In order to assess the effects of climate change it is not appropriate to compare the simulation results using climate scenarios with those of measured meteorology. Instead, simulated data for the reference scenario were used. Nevertheless it cannot be assumed, that the application of climate scenarios correctly displays the future development of carbon turnover processes, because the described systematic deviations can result in a shift of the limiting factors of the turnover. On a plot with water limitation e.g. the growth rate would not increase with increasing precipitation, if in the reference scenario a systematically underestimated radiation becomes the limiting factor instead.

Because systematic deviations always have to be expected to a more or less extent when creating climate scenarios, an analysis of the effects of these differences on the simulation results is necessary. Exemplarily, this is shown for GPP (Fig. 38). For the majority of the plots the deviations are small, but on plot BE0015 the GPP is reduced by 50 %.

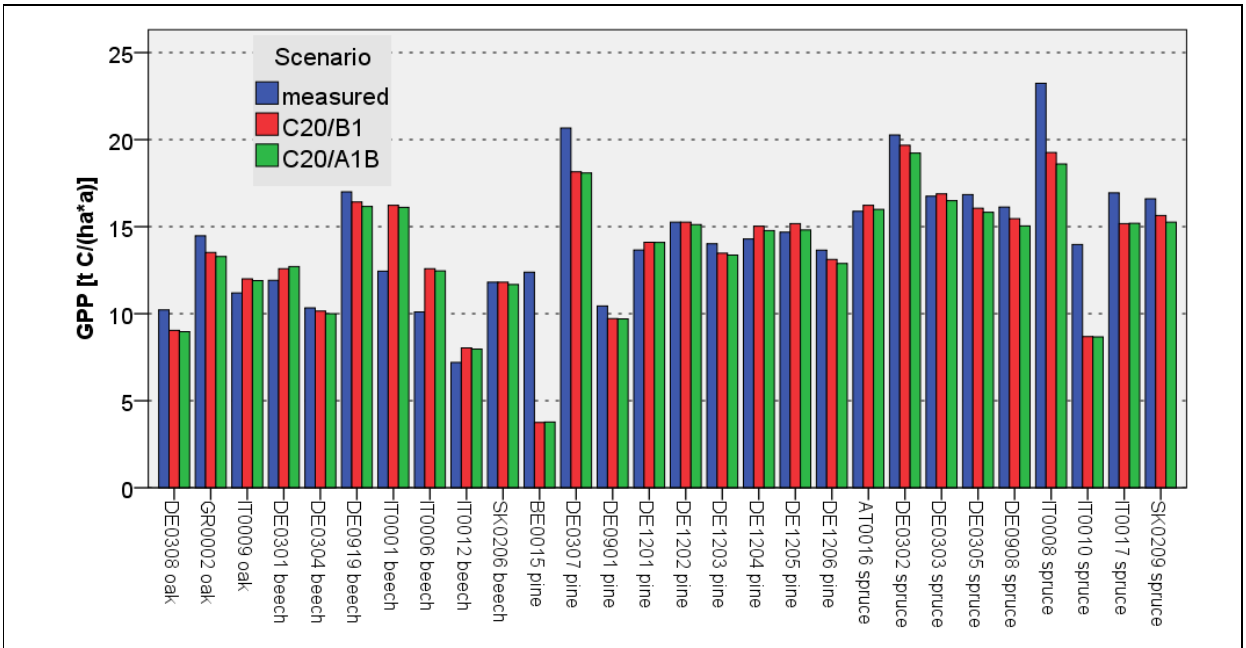


Fig. 38 Simulated plotwise averages of GPP based on the reference climate scenario compared to results based on measured meteorological data over 1996-2009

As the climate conditions have a dominating influence on the primary production, effects are expected to be dependent on the source of applied climate scenarios. It is obvious from the comparison of two different regional climate models, that the precipitation from the CLM data for plot DE1201 e.g. is significantly higher than from WETTREG (Fig. 39). Additionally, they rise over the time, while the precipitation from WETTREG decreases. These deviations may have drastic effects on the simulated GPP. The increase of GPP is much higher with simulations using CLM data than on basis of WETTREG data. For modelling climate change effects in biogeochemical cycles the use of data from ensembles of several global climate models (GCM) combined with several regionalization models is recommended.

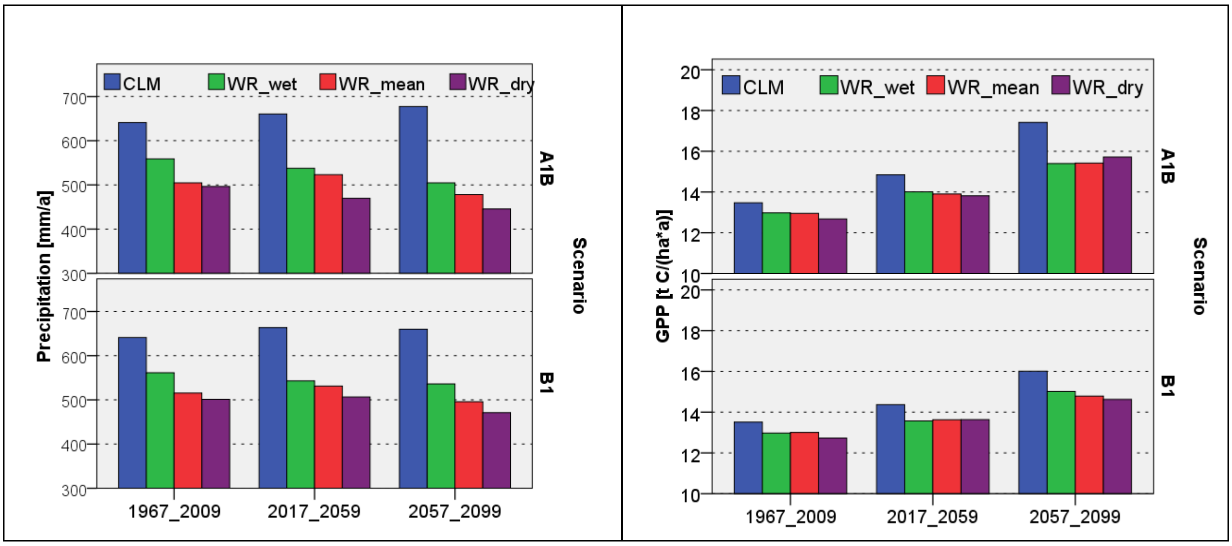


Fig. 39 Effects of the use of different climate scenario data on simulated GPP of plot DE1201. The precipitation of the FutMon_CLM data and three realizations (wet, mean, dry) of the WETTREG regionalisation model (WR) for climate scenarios are compared.

4.2.5 Consequences of simulation setup for climate scenario application

For simulating the climate change effects we decided to use one of several possible approaches, where the **initial values and all other boundary conditions are kept constant** with the exception of climate data and the atmospheric CO_2 concentrations. This simulation setup results in a number of consequences. An advantage may be that this approach avoids an overlaying effect of changing tree age during a simulation over a rotation period. Thus, the simulation results have to be attributed to a comparable "model stand" under changed climate. A disadvantage of this approach is that simulation results do not show the development of the carbon source-sink function of the concrete plot taking into account the age development of the forest stand. The integration of the age development including a change of the rotation period would require knowledge on the silvicultural scenarios, e.g. from the applicable yield tables.

The indicators for carbon balance are influenced by the fact, that **no complete rotation period** is simulated for the stand. Most forest stands are in the state of older age classes. This affects the NPP, as the relation between photosynthesis and plant respiration changes over a rotation period. As the supply of litter carbon, CWDC and SOC changes during the stand development, the heterotrophic respiration rate varies with the rotation period, too. The effect of the stand development is most apparently visible concerning the NBP, because the major part of the wood harvest takes place at the end of the stand development. Therefore the results from the present study are not comparable to long-term balances.

Possibly changing **nitrogen deposition** and the effects on primary production and priming effects were as well not considered in this investigation.

4.3 Remarks on data of level II database

When applying dynamic simulation models, a large number of data for model initialization and calibration have to be used. A model application to a large number of plots is facilitated if data can be drawn from a database. Hence, even if not all parameters are included, a sophisticated database is one of the central pre-conditions for this task. Otherwise a larger number of direct contacts to data providers would considerably increase the efforts.

Some data of the database obviously contain errors caused by different factors like wrong units, missing connection to metadata, or implausibility. Some data are evidently missing although they originate from projects under the ICP Forests program. The different reasons cannot be discussed here. Feedback from the data evaluating experts in the context of this study provided input for the continuous update and improvement of the level II data base.

Some of the level II plots are part of other monitoring programs and networks (for instance Euroflux, CarboEurope, NitroEurope, LTER, ICP-IM, ICOS) or other studies. Some of these could contribute valuable additional data for modelling (e.g. transpiration, soil respiration, NEE, root turnover …). Networking between these networks has just begun and should in future facilitate easier and enhanced use of data originating from different programmes (Clarke et al. 2011, Fischer et al. 2011).

5 Conclusions

By calibrating the simulation model Biome-BGC with level II data, a well-founded calculation of carbon budgets of different forest stands has become available. Furthermore, based on a successful calibration the modified Biome-BGC model has been proven to be a useful tool to assess climate change effects on forest ecosystems.

Simulation results on carbon budget

Under current climate conditions the simulated forests mainly act as carbon sinks. With one exception a positive net ecosystem production (NEP, on average 2.71 t C ha^{-1} a^{-1}) was simulated, denoting the forests as a carbon sink. Taking into account carbon exports by harvest, an average net biome production (NBP) of 1.8 t C ha^{-1} a^{-1} was calculated.

Under future climate conditions the carbon sink function of all ecosystems was simulated to increase. Depending on the period of observation and the applied climate scenario, a plus of 0.24 – 0.65 t C ha^{-1} a^{-1} for NEP corresponding to 10 – 26 % and an increase of 0.22 – 0.58 t C ha^{-1} a^{-1} for NBP equivalent to 13 – 35 % was calculated.

Carbon losses caused by ecosystem disturbances like diseases, insect attacks, wind throw, or forest fire are not considered by the model. For this reason the simulated carbon balance has rather to be regarded as potential carbon sequestration.

How reliable are the simulation results?

Considering the currently measured parameters and their quality as well as the general features of simulation models, the following conclusions can be drawn:

The simulation results on water budget and on the aboveground parts of carbon budget can be described adequately by the model for the current climate conditions, because the model could be calibrated by a number of measurements.

The simulation results on the belowground part of the carbon budget have to be regarded as relatively uncertain because only few calibration data were available. For litter and soil carbon stocks, coarse woody debris and roots no reliable time series exist, which could be used to initialize and calibrate the model. For this reason the simulated belowground carbon fluxes mainly rely on model parameters based on literature values for root turnover and soil respiration.

Concerning the impact of climate change on the carbon balance of forests, uncertainties due to the variation of different climate scenarios have to be considered. Additionally, predicted global radiation for the reference period of climate scenarios systematically deviate from measured values.

Interrelations between data and modelling

The monitoring data from the ICP Forests level II program, especially including the “core plots” of the FutMon project provide valuable information for calibration of dynamic simulation models for calculating the carbon budget of European forest ecosystems. The use of level II data could be seen as an intermediate step between the ICP Forests level I plots with its representativeness for Europe’s forests and the few even more intensive studies based on forest sites using Eddy covariance techniques at flux towers for NEP measurements.

As the carbon budget cannot completely be measured; modelling can contribute to fill these gaps.

Simulation of carbon budgets using measured data presupposes an intensive analysis of data and helps to find inconsistencies and to improve data quality.

The results offer valuable input for further model development.

Recommendations

In order to assess the reliability of the results it is recommended to carry out

- uncertainty analyses,
- sensitivity analyses,
- simulations using an ensemble of climate projections (different global climate models and regionalization models)
- and comparisons of different simulation models.

In order to enhance the reliability of carbon budget modelling it is recommended to

- verify the content of the database and complete the datasets
- produce gap filled meteorological datasets
- carry out additional measurements on xylem sap flow, soil respiration, root turnover, time series of SOC and CWDC, number of needle age classes, and NEP. Such assessments were not foreseen within FutMon.
- calibrate models using data from Eddy flux towers as an additional source,
- and implement some additional modules (fructification, disturbance, bioturbation, wood products) into the Biome-BGC model.

In order to extend the purpose of modelling it is recommended to

- take into account longer time periods including overlapping rotation periods by using additional information on yield tables and management scenarios applicable for the level II stands,
- consider different scenarios of future nitrogen deposition,
- include wood products turnover into the carbon balance,
- and apply calibrated models to Level I plots for representative simulation results of Europe's forests.

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7 Annex

Tab. A 1 Meteorology for the measurement period and the future and reference periods of the climate projections of the level II plots (averages of denoted periods)

plot	time period	scenario	Tmin (°C)	Tmean (°C)	Tmax (°C)	precipi-tation (mm/a)	precipi-tation days (%)	rel. humidity (%)	global radiation (W/m²)
AT0016	1994-2010	meas.	1.0	4.1	8.0	1153	52	75.5	126.7
		C20/A1B	0.9	4.8	9.3	1470	98	84.8	98.3
		C20/B1	0.9	4.7	9.1	1544	98	85.5	97.4
	1990-2009	A1B	0.8	4.7	9.2	1459	98	84.8	97.8
		B1	0.8	4.6	9.0	1532	98	85.5	97.0
	2040-2059	A1B	2.2	5.9	10.2	1629	98	86.0	95.5
		B1	2.6	6.3	10.8	1618	98	85.1	98.1
	2080-2099	A1B	3.5	7.4	12.0	1633	98	84.3	100.4
		B1	4.9	8.7	13.4	1617	97	83.3	102.3
BE0015	1996-2010	meas.	7.3	10.7	13.9	969	49	80.2	115.3
		C20/A1B	7.0	10.1	13.6	831	39	88.0	78.9
		C20/B1	7.0	10.0	13.5	830	39	88.2	78.6
	1990-2009	A1B	7.0	10.0	13.5	811	38	87.9	79.3
		B1	6.9	10.0	13.5	806	39	87.9	79.4
	2040-2059	A1B	8.0	10.9	14.3	856	40	88.6	76.9
		B1	8.5	11.5	15.0	851	38	87.8	78.4
	2080-2099	A1B	9.0	12.1	15.7	820	38	87.0	79.0
		B1	10.0	13.2	16.9	844	36	86.5	79.1
DE0301	1999-2009	meas.	5.3	9.4	13.6	817	68	80.6	107.8
		C20/A1B	6.6	9.5	12.7	974	42	95.0	84.7
		C20/B1	6.7	9.5	12.6	960	43	95.4	82.5
	1990-2009	A1B	6.5	9.4	12.6	912	41	94.9	84.8
		B1	6.5	9.4	12.6	905	42	95.2	83.5
	2040-2059	A1B	7.7	10.4	13.5	960	43	95.4	82.1
		B1	8.1	10.9	14.1	994	44	95.2	82.6
	2080-2099	A1B	8.7	11.6	14.8	964	43	94.5	83.4
		B1	9.7	12.6	15.8	990	42	94.5	82.0
DE0302	1997-2009	meas.	4.2	7.1	10.4	1388	74	87.1	121.5
		C20/A1B	4.6	7.5	10.8	1919	41	86.4	94.1
		C20/B1	4.6	7.4	10.6	1959	42	86.9	91.4
	1990-2009	A1B	4.6	7.5	10.9	1863	40	86.3	94.6
		B1	4.6	7.4	10.7	1889	41	86.6	92.9
	2040-2059	A1B	5.7	8.5	11.7	2087	43	87.0	91.7
		B1	6.2	9.0	12.2	2204	44	86.9	92.2
	2080-2099	A1B	6.8	9.7	13.1	2159	43	86.2	94.2
		B1	7.8	10.7	14.1	2198	43	86.2	92.4

Tab. A 1 (continued) Meteorology for the measurement period and the future and reference periods of the climate projections of the level II plots (averages of denoted periods)

plot	time period	scenario	Tmin (°C)	Tmean (°C)	Tmax (°C)	precipi-tation (mm/a)	precipi-tation days (%)	rel. humidity (%)	global radiation (W/m²)
DE0303	1997-2009	meas.	4.2	7.0	10.3	1388	74	87.2	122.3
		C20/A1B	4.2	7.0	10.1	1277	47	84.4	109.6
		C20/B1	4.2	6.9	9.9	1308	48	84.9	106.2
	1990-2009	A1B	4.2	7.0	10.1	1240	46	84.3	110.3
		B1	4.1	6.9	10.0	1260	46	84.6	108.2
	2040-2059	A1B	5.3	8.0	11.0	1374	49	84.9	106.8
		B1	5.8	8.4	11.5	1448	50	84.8	107.4
	2080-2099	A1B	6.4	9.2	12.4	1421	49	84.1	110.0
		B1	7.4	10.2	13.4	1440	49	84.1	108.0
DE0304	1976-2009	meas.	3.9	7.1	10.8	1134	56	83.5	98.9
		C20/A1B	3.3	6.9	10.8	1207	45	90.6	91.4
		C20/B1	3.3	6.8	10.7	1219	45	90.8	90.5
	1990-2009	A1B	3.2	6.7	10.6	1204	45	90.7	90.4
		B1	3.2	6.7	10.5	1225	46	91.0	88.7
	2040-2059	A1B	4.4	7.7	11.4	1363	48	91.5	87.3
		B1	4.8	8.2	11.9	1386	49	91.3	88.1
	2080-2099	A1B	5.4	8.9	12.8	1388	47	90.5	89.9
		B1	6.4	9.9	13.8	1442	47	90.7	88.2
DE0305	1976-2009	meas.	3.9	7.1	10.8	1134	56	83.5	98.9
		C20/A1B	3.3	6.9	10.8	1207	45	90.6	91.4
		C20/B1	3.3	6.8	10.7	1218	45	90.7	90.5
	1990-2009	A1B	3.2	6.7	10.6	1205	45	90.7	90.4
		B1	3.2	6.7	10.5	1224	46	90.9	88.8
	2040-2059	A1B	4.4	7.7	11.4	1363	48	91.5	87.3
		B1	4.8	8.2	11.9	1386	48	91.2	88.1
	2080-2099	A1B	5.4	8.9	12.8	1392	47	90.5	89.9
		B1	6.4	9.9	13.8	1441	47	90.6	88.2
DE0307	1994-2009	meas.	4.4	9.2	14.0	830	50	85.8	112.4
		C20/A1B	4.7	9.4	14.2	886	40	86.4	100.5
		C20/B1	4.7	9.4	14.1	890	41	86.6	99.6
	1990-2009	A1B	4.6	9.4	14.2	863	40	86.3	100.7
		B1	4.6	9.4	14.1	866	41	86.5	100.0
	2040-2059	A1B	5.7	10.4	15.1	898	42	86.8	98.1
		B1	6.2	10.9	15.6	952	43	86.7	98.0
	2080-2099	A1B	6.7	11.5	16.3	902	41	86.0	99.0
		B1	7.7	12.5	17.4	909	40	85.8	98.2

Tab. A 1 (continued) Meteorology for the measurement period and the future and reference periods of the climate projections of the level II plots (averages of denoted periods)

plot	time period	scenario	Tmin (°C)	Tmean (°C)	Tmax (°C)	precipi-tation (mm/a)	precipi-tation days (%)	rel. humidity (%)	global radiation (W/m²)
DE0308	1978-2009	meas.	4.1	8.5	12.9	826	87	85.6	103.6
		C20/A1B	3.9	8.1	12.4	663	35	85.4	107.7
		C20/B1	3.9	8.1	12.3	664	36	85.5	106.9
	1990-2009	A1B	3.8	8.0	12.2	684	36	85.5	106.7
		B1	3.9	8.0	12.2	685	37	85.8	105.5
	2040-2059	A1B	5.0	9.0	13.1	716	38	86.1	103.9
		B1	5.4	9.5	13.7	754	39	86.0	103.9
	2080-2099	A1B	6.0	10.1	14.3	722	38	85.5	104.1
		B1	6.9	11.1	15.3	727	37	85.5	102.9
DE0901	1991-2010	meas.	3.3	7.7	12.3	832	63	75.1	120.3
		C20/A1B	3.2	7.7	12.4	725	36	74.6	120.4
		C20/B1	3.2	7.6	12.2	742	37	75.0	118.4
	1990-2009	A1B	3.2	7.7	12.3	723	36	74.6	120.6
		B1	3.1	7.6	12.1	740	37	74.9	118.8
	2040-2059	A1B	4.3	8.6	13.1	802	39	75.6	115.8
		B1	4.8	9.1	13.6	829	40	75.1	117.1
	2080-2099	A1B	5.5	10.0	14.6	811	38	74.3	121.5
		B1	6.5	11.1	15.8	821	39	74.2	121.2
DE0908	1993-2010	meas.	3.0	6.0	9.6	911	59	79.6	116.7
		C20/A1B	2.9	5.9	9.4	896	38	78.8	116.4
		C20/B1	2.8	5.8	9.2	923	40	79.2	113.3
	1990-2009	A1B	2.8	5.8	9.4	882	38	78.6	117.0
		B1	2.8	5.7	9.2	907	39	79.0	114.4
	2040-2059	A1B	4.1	6.8	10.2	978	41	79.7	111.9
		B1	4.5	7.3	10.6	1031	42	79.4	112.7
	2080-2099	A1B	5.2	8.1	11.6	999	40	78.9	116.8
		B1	6.2	9.2	12.7	1038	41	78.8	116.6
DE0919	1994-2010	meas.	4.0	8.1	12.9	790	52	80.4	125.2
		C20/A1B	4.1	8.2	13.0	810	36	79.9	124.9
		C20/B1	4.0	8.1	12.8	842	38	80.4	122.1
	1990-2009	A1B	3.9	8.1	12.9	821	36	79.9	125.0
		B1	3.9	8.0	12.8	853	37	80.3	122.6
	2040-2059	A1B	5.1	9.1	13.7	938	40	81.1	119.3
		B1	5.6	9.6	14.2	940	40	80.6	121.3
	2080-2099	A1B	6.3	10.6	15.4	884	38	79.5	126.7
		B1	7.5	11.7	16.7	920	39	79.2	126.5

Tab. A 1 (continued) Meteorology for the measurement period and the future and reference periods of the climate projections of the level II plots (averages of denoted periods)

plot	time period	scenario	Tmin (°C)	Tmean (°C)	Tmax (°C)	precipi-tation (mm/a)	precipi-tation days (%)	rel. humidity (%)	global radiation (W/m²)
DE1201	1996-2009	meas.	3.5	8.5	13.6	619	53	85.7	111.5
		C20/A1B	3.3	8.3	13.3	640	34	86.2	107.7
		C20/B1	3.3	8.3	13.2	641	34	86.5	105.8
	1990-2009	A1B	3.2	8.2	13.2	623	34	86.2	107.5
		B1	3.3	8.2	13.1	623	34	86.4	106.2
	2040-2059	A1B	4.5	9.2	14.1	672	36	86.9	104.1
		B1	4.8	9.7	14.6	709	36	86.8	104.1
	2080-2099	A1B	5.5	10.4	15.3	669	35	86.2	104.6
		B1	6.4	11.3	16.3	689	35	86.3	104.1
DE1202	1996-2009	meas.	3.3	8.4	13.7	663	52	85.8	107.1
		C20/A1B	3.6	8.4	13.5	635	34	85.6	95.0
		C20/B1	3.6	8.4	13.4	636	34	85.9	93.2
	1990-2009	A1B	3.5	8.4	13.4	619	33	85.6	94.9
		B1	3.5	8.4	13.4	620	34	85.8	93.7
	2040-2059	A1B	4.7	9.4	14.4	664	35	86.3	91.9
		B1	5.1	9.9	14.8	705	36	86.2	91.8
	2080-2099	A1B	5.8	10.5	15.6	668	35	85.7	92.2
		B1	6.7	11.5	16.5	688	35	85.8	92.0
DE1203	1996-2009	meas.	3.4	8.6	13.7	608	51	83.8	112.1
		C20/A1B	3.4	8.5	13.4	671	34	83.1	102.3
		C20/B1	3.5	8.4	13.3	661	35	83.5	100.0
	1990-2009	A1B	3.3	8.4	13.3	658	34	83.1	102.0
		B1	3.4	8.4	13.2	651	34	83.3	100.4
	2040-2059	A1B	4.6	9.5	14.2	706	36	83.9	98.9
		B1	5.0	9.9	14.6	760	37	83.8	98.7
	2080-2099	A1B	5.6	10.6	15.5	722	35	83.2	99.1
		B1	6.6	11.6	16.5	749	36	83.2	99.1
DE1204	1996-2009	meas.	4.1	9.1	14.1	602	49	82.8	118.4
		C20/A1B	4.9	9.4	13.9	619	33	82.6	105.8
		C20/B1	4.9	9.4	13.8	616	33	82.9	103.5
	1990-2009	A1B	4.8	9.3	13.8	611	33	82.6	105.6
		B1	4.8	9.3	13.7	608	33	82.8	104.0
	2040-2059	A1B	6.0	10.4	14.7	675	35	83.4	102.3
		B1	6.4	10.8	15.1	726	36	83.4	102.3
	2080-2099	A1B	7.1	11.5	15.9	694	35	82.7	103.8
		B1	8.1	12.5	16.9	690	35	82.6	102.5

Tab. A 1 (continued) Meteorology for the measurement period and the future and reference periods of the climate projections of the level II plots (averages of denoted periods)

plot	time period	scenario	Tmin (°C)	Tmean (°C)	Tmax (°C)	precipi-tation (mm/a)	precipi-tation days (%)	rel. humidity (%)	global radiation (W/m²)
DE1205	1996-2009	meas.	3.2	8.4	13.8	623	53	84.4	114.7
		C20/A1B	3.4	8.5	13.8	617	32	84.3	106.6
		C20/B1	3.4	8.4	13.7	620	34	84.8	104.4
	1990-2009	A1B	3.3	8.4	13.7	612	32	84.4	106.7
		B1	3.3	8.3	13.6	614	33	84.7	105.1
	2040-2059	A1B	4.5	9.4	14.6	693	35	85.4	103.9
		B1	4.9	9.8	14.9	744	36	85.4	102.7
	2080-2099	A1B	5.6	10.6	15.8	702	35	84.7	104.4
		B1	6.6	11.6	16.9	714	34	84.5	103.9
DE1206	1996-2009	meas.	3.9	9.0	14.5	583	55	84.5	114.0
		C20/A1B	3.9	8.9	14.3	589	32	83.8	90.9
		C20/B1	3.9	8.8	14.1	586	32	84.2	88.7
	1990-2009	A1B	3.8	8.8	14.2	581	31	83.8	90.7
		B1	3.8	8.8	14.1	578	32	84.1	89.2
	2040-2059	A1B	5.0	9.9	15.1	638	34	84.7	88.2
		B1	5.4	10.2	15.4	683	35	84.8	87.4
	2080-2099	A1B	6.1	11.0	16.3	656	33	84.2	88.0
		B1	7.1	12.0	17.3	660	34	84.1	88.1
GR0002	1994-2010	meas.	9.3	12.1	15.0	1109	25	70.5	135.8
		C20/A1B	10.4	14.6	19.8	530	24	60.1	154.3
		C20/B1	10.5	14.7	19.9	520	24	59.6	153.8
	1990-2009	A1B	10.3	14.5	19.7	537	25	60.3	154.2
		B1	10.4	14.5	19.7	531	24	59.9	153.7
	2040-2059	A1B	11.5	15.7	21.0	528	24	59.4	154.1
		B1	11.9	16.1	21.4	478	23	58.4	154.6
	2080-2099	A1B	12.7	16.9	22.2	508	23	58.5	154.1
		B1	13.6	17.8	23.2	454	22	57.3	154.5
IT0001	1996-2010	meas.	3.0	6.1	10.0	1023	71	81.7	153.9
		C20/A1B	8.4	13.6	20.3	807	27	72.8	132.1
		C20/B1	8.4	13.6	20.3	838	27	72.7	132.2
	1990-2009	A1B	8.4	13.5	20.3	779	26	72.4	132.7
		B1	8.3	13.5	20.2	797	26	72.5	132.4
	2040-2059	A1B	9.4	14.5	21.3	822	27	72.8	130.9
		B1	9.8	15.1	22.0	758	26	71.2	134.1
	2080-2099	A1B	10.7	16.0	23.0	773	26	70.8	134.3
		B1	12.0	17.4	24.5	732	25	69.7	134.6

Tab. A 1 (continued) Meteorology for the measurement period and the future and reference periods of the climate projections of the level II plots (averages of denoted periods)

plot	time period	scenario	Tmin (°C)	Tmean (°C)	Tmax (°C)	precipi-tation (mm/a)	precipi-tation days (%)	rel. humidity (%)	global radiation (W/m²)
IT0006	1996-2010	meas.	5.3	9.4	14.5	1321	65	78.6	140.2
		C20/A1B	6.3	11.0	17.2	818	29	75.4	124.2
		C20/B1	6.2	10.9	17.2	801	29	75.2	124.0
	1990-2009	A1B	6.2	10.9	17.2	776	28	74.9	124.5
		B1	6.1	10.9	17.2	762	28	74.7	124.5
	2040-2059	A1B	7.2	11.9	18.1	853	29	75.9	122.5
		B1	7.7	12.6	19.0	765	27	73.4	126.6
	2080-2099	A1B	8.6	13.4	19.9	814	28	73.2	126.9
		B1	9.8	14.7	21.2	833	28	73.2	126.0
IT0008	1996-2010	meas.	2.8	6.7	11.6	1697	42	88.1	125.1
		C20/A1B	0.8	5.0	9.9	1615	78	82.6	106.3
		C20/B1	0.8	4.9	9.7	1764	80	83.3	105.7
	1990-2009	A1B	0.7	4.9	9.8	1606	78	82.6	105.7
		B1	0.7	4.8	9.6	1726	79	83.1	105.5
	2040-2059	A1B	2.1	6.1	10.8	1873	80	83.6	103.6
		B1	2.4	6.5	11.4	1783	79	82.3	106.7
	2080-2099	A1B	3.4	7.6	12.6	1824	79	81.4	108.9
		B1	4.8	8.9	14.0	1784	79	80.7	110.2
IT0009	1996-2010	meas.	8.1	12.0	16.9	1027	59	79.4	160.3
		C20/A1B	8.4	13.7	20.8	678	26	73.6	132.6
		C20/B1	8.3	13.6	20.7	709	25	73.7	132.5
	1990-2009	A1B	8.3	13.6	20.8	656	25	73.1	133.2
		B1	8.3	13.6	20.8	676	25	73.1	133.1
	2040-2059	A1B	9.3	14.5	21.7	730	26	73.9	130.9
		B1	9.7	15.2	22.6	659	24	71.9	134.6
	2080-2099	A1B	10.7	16.1	23.5	682	25	71.3	135.0
		B1	12.0	17.5	24.9	670	24	70.6	134.1
IT0010	1997-2010	meas.	3.7	6.9	11.5	1395	72	73.8	93.8
		C20/A1B	-1.0	2.9	7.0	1835	85	82.7	95.9
		C20/B1	-0.9	2.9	7.0	1937	86	82.7	96.5
	1990-2009	A1B	-1.0	2.8	6.9	1867	86	83.0	95.2
		B1	-1.0	2.9	6.9	1922	87	82.9	95.8
	2040-2059	A1B	0.3	4.0	8.0	2143	87	83.5	95.2
		B1	0.8	4.7	9.0	1955	86	81.6	100.8
	2080-2099	A1B	1.7	5.7	10.1	1991	86	81.0	102.9
		B1	3.2	7.2	11.7	2092	85	80.3	105.9

Tab. A 1 (continued) Meteorology for the measurement period and the future and reference periods of the climate projections of the level II plots (averages of denoted periods)

plot	time period	scenario	Tmin (°C)	Tmean (°C)	Tmax (°C)	precipi-tation (mm/a)	precipi-tation days (%)	rel. humidity (%)	global radiation (W/m²)
IT0012	1999-2010	meas.	4.4	7.2	10.6	1448	58	72.9	151.7
		C20/A1B	3.9	8.3	13.7	1420	60	73.5	111.1
		C20/B1	3.9	8.4	13.7	1353	61	72.8	111.8
	1990-2009	A1B	3.7	8.2	13.5	1450	60	73.7	110.2
		B1	3.8	8.2	13.6	1414	61	73.3	110.8
	2040-2059	A1B	5.1	9.4	14.6	1713	62	74.2	109.7
		B1	5.6	10.2	15.7	1370	60	71.8	114.9
	2080-2099	A1B	6.5	11.1	16.7	1487	61	71.5	115.8
		B1	8.0	12.6	18.2	1505	61	70.9	117.5
IT0017	1997-2010	meas.	-0.3	4.5	9.9	1029	63	70.3	149.3
		C20/A1B	-1.2	3.1	7.8	1340	73	81.9	105.0
		C20/B1	-1.1	3.2	7.8	1421	74	82.0	106.0
	1990-2009	A1B	-1.2	3.1	7.7	1352	74	82.1	104.4
		B1	-1.1	3.1	7.7	1406	74	82.1	105.2
	2040-2059	A1B	0.2	4.3	8.8	1553	74	82.7	104.3
		B1	0.7	5.0	9.7	1415	72	80.6	109.2
	2080-2099	A1B	1.6	5.9	10.8	1439	70	80.1	110.9
		B1	3.2	7.4	12.4	1481	68	79.1	113.9
SK0206	1999-2010	meas.	4.0	8.2	11.8	723	35	83.7	128.1
		C20/A1B	2.9	7.0	11.8	780	31	83.4	98.4
		C20/B1	2.8	6.7	11.2	861	32	85.0	94.8
	1990-2009	A1B	2.7	6.8	11.5	759	30	83.4	98.1
		B1	2.7	6.7	11.2	809	31	84.4	95.8
	2040-2059	A1B	4.1	7.9	12.4	895	34	84.9	95.3
		B1	4.3	8.2	12.7	891	35	84.7	95.5
	2080-2099	A1B	5.3	9.3	14.0	879	33	83.1	98.9
		B1	6.3	10.3	15.1	872	33	82.6	98.8
SK0209	1999-2010	meas.	3.5	6.7	10.7	1241	94	84.9	98.6
		C20/A1B	3.4	6.9	10.8	945	39	86.9	88.3
		C20/B1	3.3	6.6	10.3	1013	42	88.2	84.5
	1990-2009	A1B	3.2	6.7	10.6	928	38	86.9	88.1
		B1	3.2	6.6	10.3	970	40	87.7	85.6
	2040-2059	A1B	4.6	7.8	11.4	1025	43	87.9	84.5
		B1	4.8	8.1	11.7	1067	45	88.1	84.3
	2080-2099	A1B	5.7	9.0	12.8	1035	43	87.0	87.6
		B1	6.7	10.1	13.9	1062	44	86.8	87.4

Tab. A 2 Simulation results on water fluxes of the level II plots using climate data of future and reference periods

Plot	Period	Scenario	Precipi-tation	Stand precip-itation	Canopy evaporation	Soil evaporation	Transpi-ration	Outflow
AT0016	1990-	C20/B1	1458	903	555	9	368	521
	2009	C20/A1B	1531	954	577	9	362	578
	2040-	B1	1628	964	664	8	349	602
	2059	A1B	1617	939	678	7	355	572
	2080-	B1	1632	925	707	7	367	545
	2099	A1B	1615	827	789	5	343	479
BE0015	1990-	C20/B1	810	730	80	217	35	484
	2009	C20/A1B	806	725	81	221	35	475
	2040-	B1	857	761	96	192	40	536
	2059	A1B	851	740	111	162	60	531
	2080-	B1	820	709	110	159	65	500
	2099	A1B	844	726	118	147	71	527
DE0301	1990-	C20/B1	912	711	201	58	223	429
	2009	C20/A1B	904	700	203	56	221	422
	2040-	B1	960	746	214	55	203	488
	2059	A1B	993	779	214	54	209	516
	2080-	B1	964	759	206	51	215	492
	2099	A1B	990	793	197	51	199	542
DE0302	1990-	C20/B1	1239	908	332	4	309	593
	2009	C20/A1B	1259	925	335	4	303	615
	2040-	B1	1374	1003	371	3	283	716
	2059	A1B	1447	1052	395	3	285	764
	2080-	B1	1421	1022	399	3	288	732
	2099	A1B	1440	1041	399	3	253	786
DE0303	1990-	C20/B1	1239	916	323	3	272	639
	2009	C20/A1B	1259	933	326	3	265	664
	2040-	B1	1374	1012	362	3	248	761
	2059	A1B	1447	1067	381	3	252	812
	2080-	B1	1421	1038	382	3	259	777
	2099	A1B	1440	1050	390	2	232	816
DE0304	1990-	C20/B1	1204	921	282	76	302	527
	2009	C20/A1B	1224	942	282	79	294	555
	2040-	B1	1363	1067	296	78	282	701
	2059	A1B	1385	1092	293	77	289	721
	2080-	B1	1388	1105	283	75	305	721
	2099	A1B	1441	1169	273	75	294	799
DE0305	1990-	C20/B1	1205	810	395	9	290	509
	2009	C20/A1B	1223	822	401	9	287	524
	2040-	B1	1363	922	440	8	261	651
	2059	A1B	1384	928	456	8	264	655
	2080-	B1	1392	933	460	7	276	649
	2099	A1B	1441	974	467	7	241	725