



# Report

## **Biome-BGC model analysis and application in the USA**

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# 1 Introduction

The basic inducement to go to the USA for five months was the opportunity to present, work on and apply recent Biome-BGC model improvements. This could be done at the University of Missoula, Montana, the place where the model was first developed, and at the Oak Ridge National Laboratory in Oak Ridge, Tennessee. Two main academic institutions currently work on the improvement of the model and its adaptation to a search for answers on some of the most pressing questions in today's forest ecology. These are the University of Missoula, i.e. the NTSG and the Institute of Silviculture at University of Natural Resources and Applied Life Sciences, Vienna, the place where I currently work.

Some of the questions addressed are the impact of projected climate change and concurrent changes in the functioning and performance of forests. The ecosystem model Biome-BGC can serve as a diagnostic and predictive tool for quantifying effects of a changing atmospheric/climatic environment and forest management. Variations in the carbon- and nutrient cycle and water fluxes of a forest ecosystem have always occurred due to fluctuations in the climatic conditions and with the aging, the maturation and senescence of the forest. The dependence on the daily weather and certain environmental factors varying over longer timescales, i.e. atmospheric CO<sub>2</sub> content and nitrogen deposition, needs to be incorporated in an ecosystem model in a mechanistic way in order to be able to analyze and predict forest behavior under new environmental conditions. Biome-BGC is a prognostic model, which means that no measurements at the present forest are required for the parameterization (like e.g. leaf area). On the other hand, information on the past forest situation and management and a sound parameterization of the tree species is essential for the simulation of the current forest stand. A good representation of today's situation is necessary for any studies on future forest development. The objective of my stay in the USA was to bring together modeling knowledge from both working groups and use this modeling platform for a first climate change impact study, with the focus on the forest water budget. This study could be conducted with extensive environmental and ecophysiological data on a free-air-CO<sub>2</sub>-enrichment (FACE) experiment running for 12 years at the Oak Ridge National Laboratory and results will be presented in this report. At the moment, also a paper with the study results is in preparation (Wullschleger, Warren, Pötzelsberger, Thornton and Norby, in prep.). Therefore, it is not possible for me to present the full amount of data/results and the according explanations and discussions in this report. Some chapters consequently are shorter than originally planned and I will refer to that future publication sometimes in this report.

All this work is expected to considerably improve the performance of the model for future climate change studies, such as my main PhD-project on climate change impacts on (European Beech) forests in the West-Pannonian Basin. In the future more analysis of these data from the Oak Ridge FACE site linked with simulations and further model improvements is planned.

## **2 The Biome-BGC model**

In this study we used the process based ecosystem model BIOME-BGC, version 4.1.1 (Thornton et al., 2002), incorporating an extension on the model self initialisation that uses a dynamic mortality routine (Pietsch and Hasenauer, 2006).

Fluxes and cycles of energy, water, carbon and nitrogen in a forest ecosystem are simulated in a fully prognostic mode on a daily time resolution. Model drivers are daily weather data, i.e. minimum and maximum temperature (tmin and tmax), solar shortwave radiation, vapour pressure deficit and precipitation (prcp), which were calculated from hourly data available for the site from 1998 to 2008 (Riggs et al., 2009). Forest type / tree species, disturbance history, forest management, soil physical properties, atmospheric carbon dioxide content and nitrogen deposition are furthermore decisive influences on the simulated ecosystem processes.

The daily simulations most importantly calculate:

- daily canopy rainfall interception, evaporation and canopy dripping
- soil evaporation, water potential, outflow and water content
- Leaf Area Index (LAI) ( $\text{m}^2$  leaf area per  $\text{m}^2$  ground area)
- stomatal conductance to water and  $\text{CO}_2$
- transpiration
- assimilation of sun-lit and shaded canopy fractions
- Gross Primary Production (GPP), autotrophic respiration and Net Primary Production (NPP)
- allocation of carbon and nitrogen to the different ecosystem compartments (soil, litter, roots, stem, leaves, storage)
- mortality
- litter fall and decomposition
- mineralisation, denitrification, leaching and volatile nitrogen losses.

The LAI controls canopy radiation absorption, water interception in the canopy, photosynthesis and litter inputs to the detrital pools.

Photosynthesis calculations are separately done for sun and shade leaves and use the Farquhar photosynthesis regime and kinetic constants of Woodrow and Berry (1988), de Pury and Farquhar (1997) as well as parameters from Wullschleger (1993) and Kuehn and McFadden (1969). Potential gross primary production will be reduced in case of nitrogen limitation and consequential competition between mineralizing microorganisms and plants. In this case available mineral nitrogen will be equally split according to the plant and microorganism nitrogen demand. Plant nitrogen demand is derived from the potential amount of carbon allocated to different tissues and the tissue's carbon to nitrogen (C/N) ratio. Microbial nitrogen demand depends on potential mineralisation - which itself depends on the amount of available substrate, soil temperature and moisture -, the C/N ratio of the substrate and of the soil organic matter pool into which the material is converted and the amount of carbon lost through respiration. Gross primary production (GPP) ( $\text{kg C.m}^{-2}$ ) then is the rate of photosynthesis minus the daytime leaf maintenance respiration, a function of leaf nitrogen concentration (Ryan, 1991) and day length. Net Primary Production (NPP) is the difference between GPP and autotrophic respiration. Autotrophic respiration is summed up from (i) plant maintenance respiration, a function of tissue nitrogen content and temperature, and (ii) growth respiration, which is set after Larcher (1995) to 30% of new carbon available for allocation. This means that growth respiration for carbon that is stored trees is calculated at the time of entering the storage pool and not at display during the following growing season. For evergreen forests this issue does not relevant since no carbon gets stored.

NPP is partitioned into the different plant compartments as a function of fixed species / plant functional type specific allocation patterns (see also paragraph 3.2.2.2.5). The total ecosystem carbon storage results from the balance between NPP and heterotrophic respiration, which is regulated by decomposition activity, the seasonal input of vegetation biomass into litter and soil organic matter pools and the annual mortality rate.

In addition to these daily during the growing season calculated carbon and nitrogen fluxes some more timely constrained processes need to be addressed in case of deciduous trees, i.e. the time of leave development in spring and litterfall in autumn. Both periods are defined as fractions of the growing season (see also paragraphs 0 and 3.2.2.2.2). The first day of new growth is set to the 15<sup>th</sup> day before the day when the summation of daily soil temperatures  $> 0^{\circ}\text{C}$  reaches an empirically defined critical value. This value depends on the long term mean daily average temperature (White et al., 1997) and the soil temperature is calculated as a

linearly ramped 11 day running average of daily mean air temperature. During the leaf onset period carbon and nitrogen that were stored in the previous year get finally displayed. This is also true for carbon and nitrogen stored for stem and root growth. The final day of litterfall period is either set to the 15<sup>th</sup> day after the day when the day length falls below the critical day length of 39300 seconds and the soil temperature is smaller or the same as the long term average soil temperature between the 244<sup>th</sup> and the 305<sup>th</sup> day of the year or to the 15<sup>th</sup> day after a day in the second half of the year when the soil temperature falls below 2°C. During the litterfall period some leaf nitrogen is allocated into a storage pool. The amount is determined by the difference in leaf and litter C/N ratios and the size of the leaf nitrogen pool. The remaining nitrogen and all the leaf carbon are added to the leaf litter pools.

For the decomposition of leaf litter and other dead plant material like coarse woody debris these materials are split up into their chemical components, i.e. labile fraction (hot water and alcohol soluble), hemicellulose / cellulose (acid soluble) and a recalcitrant fraction (acid insoluble) and added to the three according litter pools.

Next to carbon and nitrogen, water is the third main component that's cycling is addressed in the model. Rainfall is partly intercepted by the canopy, depending on the LAI and an interception coefficient and the rainfall intensity and partly goes directly to the soil water pool. The canopy water either evaporates on the same day or, if the not all the intercepted water can be evaporated, is added to the soil water pool, to represent canopy dripping. Evaporation is calculated with the Penman-Monteith equation (Monteith, 1965) as a function of air temperature, air pressure, vapour pressure deficit (VPD), incident solar radiation and the transport resistance of water vapour and sensible heat (Jarvis and McNaughton, 1986). In case of temperatures below 0°C precipitation is assumed to fall as snow, which is immediately added to the snowpack. Snow melts when the daily average temperature is positive with a temperature coefficient of melting of  $0.65 \text{ kg m}^2 \text{ }^\circ\text{C}^{-1} \text{ d}^{-1}$ . Besides, also solar irradiation can cause water to go from the solid phase into the liquid phase when temperatures are positive. In addition, solar irradiation induces sublimation of water at freezing temperatures.

Water added to the soil water pool either drains or is stored and taken up by plants and transpired or evaporates. The total soil water holding capacity at saturation can be determined from the total effective soil depth – soil depth minus the stone fraction > 2mm – and the texture with empirical formulations after Clapp and Hornberger (1978), Saxton et al. (1986) and Cosby et al. (1984). For the outflow treatment it is also necessary to know the volumetric



water content at field capacity, where field capacity is defined as  $-0.015\text{MPa}$  (Thornton 1998). Water that is above saturation is lost immediately and water between saturation and field capacity is lost at a rate of 50% per day. Remaining soil water is then available to plant uptake or can get evaporated. Plant water uptake is driven by the demand of water for transpiration, where transpiration is regulated by stomatal opening by the plant and is, as evaporation, calculated with the Penman-Monteith equation. For the stomatal conductance the model of Jarvis (1976) is applied, where reduction factors lower a maximum stomatal conductance. With the reduction factors the influence of solar radiation, vapour pressure deficit, leaf / soil water potential and temperature on the stomatal conductance is addressed. The stomata response to solar radiation is described as a hyperbolic function, with the half saturation value generally set to  $75 \mu\text{mol m}^{-2} \text{s}^{-1}$  after Körner (1995) who gives a range of values between 50 and  $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ . The other reduction factors are linear functions of the VPD, the soil water potential – a surrogate for the predawn leaf water potential and the daily minimum temperature, where a starting and an end value for the stomatal reduction are needed. They are defined in the epc (ecophysiological constants) -file of the simulated vegetation type. Stomatal response to atmospheric  $\text{CO}_2$  content is not yet explicitly addressed in the model. However, in order to account for reduced stomata opening under elevated  $\text{CO}_2$  we decided to choose a lower maximum value for stomatal conductance (see also paragraph 3.2.2.2.10). The calculation of the total leaf level conductance follows the electrical circuit analogy of Nobel (1991), with stomatal and cuticular conductance in parallel and leaf boundary layer conductance in series.

This model version uses the dynamic mortality scheme of Pietsch and Hasenauer (2006) for the spin-up run and a constant mortality afterwards. The authors found that a constant annual mortality, as it was used in the model spin-up before, results in an overestimation of total carbon stocks when comparing a virgin forest with simulation results from the spin-up run. Their conception was that both, the virgin forest and the last phase of the spin-up run, represent forest ecosystems in a dynamic equilibrium. A virgin forest typically is not a homogenous forest with a constant mortality but is composed of small forest patches in different stages of the forest development cycle - stand establishment, juvenile stage, maturity, senescence and break down phase – with a higher mortality in the young forest, a lower mortality during the optimum growth phase and a higher mortality again towards the end of the cycle. With a constant mortality of 0.5% in the spin-up run the total carbon stocks were overestimated by 400%. After choosing an annual mortality rate of 3% unbiased stem

carbon predictions could be achieved, but the dead biomass and the soil carbon pools were still overestimated. Increasing the rates of decomposition turnover didn't result in a sufficient reduction in these two pool sizes. Unbiased predictions could only be achieved after introducing an elliptic mortality routine.

So far, this kind of spin-up analysis has only been done for European Beech. But also in simulation-studies on different species this dynamic mortality routine has been and also will be used by our working group at the BOKU University, since up to now I am not aware of any arguments that would clearly contradict this dynamic mortality concept. Neither from the other main Biome-BGC modeling group at the University of Missoula, Montana, nor from Peter Thornton doubts on the theory or the simulation procedure have been issued. Therefore, the Biome-BGC model including this spin-up extension could directly applied for the Oak Ridge FACE site simulation study, which will be presented in this report.

For further details to model calculations I refer to Thornton (1998), Thornton et al. (2002), White et al. (2000) and Pietsch and Hasenauer (2006).

General model operation:

The Biome-BGC model is fully prognostic and therefore needs a self initialization, or as often termed, spin up run to reach a quasi-equilibrium of the carbon and nitrogen pools of the simulated vegetation with the site conditions (weather, soil, atmosphere). For the whole simulation process the set of available weather data is used again and again. The model is spun up from an initial state, i.e. with minimal carbon in leaves ( $0.01 \text{ kgC/m}^2$ ) and in stem ( $0.025 \text{ kgC/m}^2$ ) and a half water saturated soil to a quasi-equilibrium. At this stage the soil carbon content, as the last pool to reach a dynamic equilibrium, does not change more than  $0.0005 \text{ kgC/m}^2/\text{yr}$  between two full forest life / mortality cycles (sum of length of low mortality phase and length of high mortality phase, see paragraph 3.2.2.2.4 for more details).

After the model was initialized the historic land use at the site is simulated to account for soil degradation effects caused by repeated land clearings and new forest establishment or for changes in forest type / tree species and according changing quality of litter and woody debris input (Pietsch and Hasenauer, 2002). In the final phase of the simulation the actual stand gets established / planted and grows until it reaches its current age. Management, i.e. thinning of the stand can be considered.

### **3 Model application for the Oak Ridge FACE experiment**

The Oak Ridge FACE experiment, with FACE as an abbreviation for ‘Free Air CO<sub>2</sub> Enrichment’, is a scientific forest manipulation study, where plantations of American Sweetgum are fumigated with extra CO<sub>2</sub> causing an atmospheric CO<sub>2</sub> content of approximately 550 ppm. This value is anticipated for the middle of the 21<sup>st</sup> century if no significant measures to cut greenhouse gas emissions will be undertaken. During the 12 years of operation responses of the forest to the treatment are observed and measured in all ecosystem compartments. Some of the responses were expected, some came as a surprise and explanations for changes in forest behavior are partly available in the recent literature. In such a case the investigation of the experiment with an ecosystem model can help finding cause-response relationships and bridge the gap between single measurements at the site. The later is especially true for process based recursion models, where pools of the main matter-constituents in the different ecosystem compartments and fluxes among these pools caused by model drivers are simulated. Therefore, the Biome-BGC model was decided on to be employed to mathematically reproduce the experiment and to help to understand some measurements results. On the other hand, deficiencies in the model logic may get apparent by an in depth comparison of simulations with detailed measurements and eventually the integration of study results can lead to advancements in the model algorithms.

In this study we put special emphasis on the analysis of the water budget at the Oak Ridge FACE forest plots. Daily transpiration measurements over three growing seasons (1999, 2004 and 2008), stomatal conductance and photosynthesis studies, all-season LAI-curves for all plots for the whole treatment period and a measured soil water retention curve were water budget related experiment outputs available for this study. We therefore could conduct some interesting comparisons of observations with the according components of the water budget model for the experimental plots. The final results of these detailed comparisons cannot be presented in this report, since they constitute unpublished data. A scientific paper is under preparation, though.

### 3.1 The Oak Ridge FACE site

#### 3.1.1 The Oak Ridge FACE experiment

The Oak Ridge FACE experiment is a free air CO<sub>2</sub> enrichment experiment conducted at an American Sweetgum (*Liquidambar styraciflua* L.) tree plantation established in Oak Ridge National Environmental Research Park in eastern Tennessee (35° 54' N; 84° 20' W). One-year-old Sweetgum seedlings of this native (see Figure 3) deciduous tree were planted in 1988 at 2.3 x 1.2 m spacing on previously cultivated alluvial land along the Clinch River. The soil is an Aquic Hapludult with a silty-clay-loam texture. A survey of the site in 1998 indicated that the 10-yr-old plantation had an average height of 12 m and an average leaf area index of 5.5 m<sup>2</sup> m<sup>-2</sup>.



**Figure 1 Oak Ridge FACE site around 1998: American Sweetgum plantation with four 25m diameter experimental plots circled by vertical vent pipes; Today the trees reach to the top of the pipes. Source: [http://public.ornl.gov/face/ORNL/ornl\\_home.shtml](http://public.ornl.gov/face/ORNL/ornl_home.shtml).**

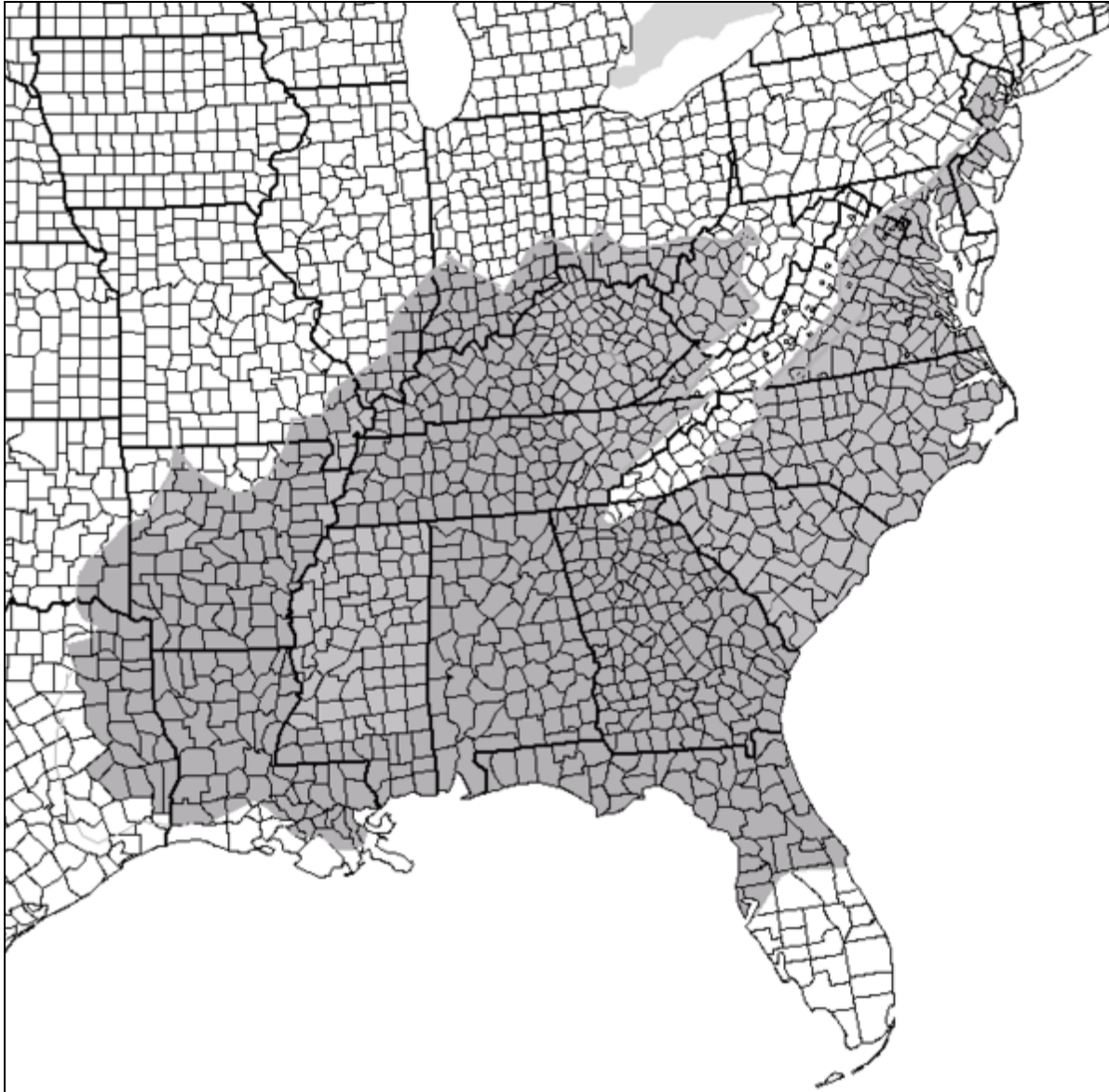


A free air CO<sub>2</sub> enrichment (FACE) system was installed at the site in five 25-m-diameter plots in 1997. The FACE system controls the release of CO<sub>2</sub> from vertical PVC vent pipes located around each plot. In Figure 1 four of these plots can be discerned by the vent pipes arranged around these 25-m-diameter plots. Today the trees already reach up to the top of these pipes and even higher. Two of these pipes and the small openings through which the CO<sub>2</sub> is released can be seen in Figure 2. The gassing can be regulated based on wind speed, wind direction, and *in situ* measurements of current CO<sub>2</sub> concentration within the canopy (Hendrey et al., 1997). Since 1998, elevated CO<sub>2</sub> has been released in two plots during each growing season, while ambient air was circulated in the two of the three control plots. The atmospheric CO<sub>2</sub> concentration in the elevated plots was maintained in the target span of 525-555 ppm during the growing season. This means, the CO<sub>2</sub> concentration was about 40% higher than in the ambient plots (380-400 ppm).



**Figure 2** Vertical vent pipes through which the CO<sub>2</sub> is released at the Oak Ridge FACE site. In the picture Peter Thornton (left) and Jeff Warren (right, geared up for climbing the tower in the middle of the picture to harvest branches for a lab experiment) can be seen.

The mean annual temperature (1962-93) at the study site is 13.9 °C and annual precipitation averages 1371 mm. Precipitation in the area is generally distributed throughout the year; however, occasionally there are 3 to 5-week periods of significant water deficit during late summer.



**Figure 3** Natural distribution range of the American Sweetgum Liquidambar styraciflua in the United States. Source: [http://en.wikipedia.org/wiki/Liquidambar\\_styraciflua](http://en.wikipedia.org/wiki/Liquidambar_styraciflua), based on a map given in Burns et al. (1990).

### **3.1.2 Some measurements from the Oak Ridge FACE site relevant for this study:**

Climate data were collected during the whole FACE experiment period with micrometeorological equipment. These measurements include precipitation, wind, photosynthetically active radiation (PAR), and air temperature and relative humidity above and beneath the canopy.

For the model parameterization measurements of further site characteristics and various stand properties were available. Measurements and study results got published during the last years and/or are available at the webpage of the FACE Data Management System ([http://public.ornl.gov/face/ORNL/ornl\\_home.shtml](http://public.ornl.gov/face/ORNL/ornl_home.shtml)).

Net primary productivity (NPP) of the plots was derived on an annual basis from independent measures of leaf, wood, and fineroot production (Norby et al, 2002). The procedures are mainly described in Norby et al. (2001). Leaf litter production was calculated from litter trap collections. Net wood production was determined using an allometric equation that relates aboveground woody biomass increment to the change in basal area of each individual tree and to plot-averaged measurements of stem height, taper, and wood density. Coarse-root production was determined through an allometric equation relating root mass to tree basal area. Annual fineroot production was determined using minirhizotrons, camera, and digitizing (Norby et al. 2004). A couple of minirhizotrons per plot were surveyed every two weeks. Based on specific root length and scaling factors, the data on fineroot length production, mortality, and standing crop per tube were converted to mass per land area. An improved relationship between length and mass and better data on overwinter production and mortality is described in Iversen et al. (2008).

Canopy transpiration was derived from sap flow measurements. The sap flow for four trees in each of two ambient and elevated CO<sub>2</sub> plots (16 trees in total) was measure with compensated heat-pulse technique in 1999 and 2004. A single heat-pulse probe was positioned in the sapwood of each tree at a depth of 19 mm. A heat pulse was provided for 1.8 s and measurements were recorded every 60 min. Sap velocity could be calculated from corrected heat pulse velocity. For all the details the reader shall be referred to Wullschleger and Norby (2001). Sap flow in 2008 was quantified using thermal dissipation probes installed at multiple depths in five trees in each of the two ambient and two elevated CO<sub>2</sub> treatment plots. The temperature difference between the heated and unheated probe was considered to be proportional to the voltage differential between the probes and can be related to sap velocity based on the empirical relationship between the voltage differential and the heat dissipation



attributed to sap flow near the heated probe. Hourly rates of stand transpiration ( $\text{mm h}^{-1}$ ) were estimated as a function of measured sap velocity, total stand sapwood area, and the fraction of sapwood functional in water transport. Treatment differences in sapwood area were not observed over the course of the experiment. Daily rates of stand transpiration ( $\text{mm d}^{-1}$ ) in both years were calculated via a simple summation of hourly rates.

Probes used for the sap flow measurements can be seen in Figure 4.



**Figure 4** Thermal dissipation probes used to determine sap flow at the Oak Ridge FACE experiment. The probes were normally covered with Styrofoam and got just pulled out from the stem. A callus around the whole formed only during this growing season can be seen.



## 3.2 The Biome-BGC application

In this study we aimed at representing observed growth and water balance characteristics of the Oak Ridge FACE American Sweetgum plots with the mechanistic ecosystem model Biome-BGC, at quantifying additional non-measured ecosystem fluxes and at basically determining the whole water budget of the elevated and the ambient CO<sub>2</sub> treatment plot. Although two elevated CO<sub>2</sub> plots and three reference plots are maintained simply one simulation per treatment was done for a plot specific parameterization was not feasible lacking information on possibly different site specific parameter values. Daily weather data driving the fluxes and changes in pool sizes in this daily time step model and the site parameterization for the two ambient and elevated CO<sub>2</sub> treatment plots were essentially the same. The only differences lay in some of the ecophysiological constants derived from measurements at the site, and, of course, the atmospheric CO<sub>2</sub> content. Since the model is totally prognostic with regard to pool sizes and fluxes, in a first step the model needs to run a self initialization, afterwards historic land-use is simulated and eventually the current stands can be planted and grown up to present. For the whole simulation-process several hundreds of carbon, nitrogen and water flux and pool variables can be printed for analysis and i.e. for comparison with observations.

### 3.2.1 Model drivers

Daily weather data over several years are need as the main model drivers. Hourly data on atmospheric temperature, precipitation, relative humidity and total incident radiation were available for the years 1998 – 2008. The necessary daily model input data T<sub>min</sub>, T<sub>max</sub>, precipitation, vapor pressure deficit and shortwave solar radiation were calculated from these data. In Figure 5, 7 and 8 daily average values for T<sub>min</sub>, T<sub>max</sub>, incident solar radiation and VPD for the period 1998 – 2008 and daily values for the year 1999, the year I will later focus on for the transpiration analysis, are shown.

Lowest temperature measured during this period was -13.4 °C and highest temperature was 33.9 °C. In this region heavy rainfall events are not unusual and daily maximum precipitation can go up to 100mm and even slightly more! On average, precipitation is rather evenly distributed throughout the year, with the on average driest months October and August (compare Figure 6). Annual precipitation ranged between 900 mm (in 2007) and 1600 mm (in 2003), with an average of 1350 mm during 1998 – 2008. Highest measured vapor pressure deficit was 2495 Pa. Incident solar radiation averaged 265 W.m<sup>-2</sup>, with a maximum of 515 W.m<sup>-2</sup>.

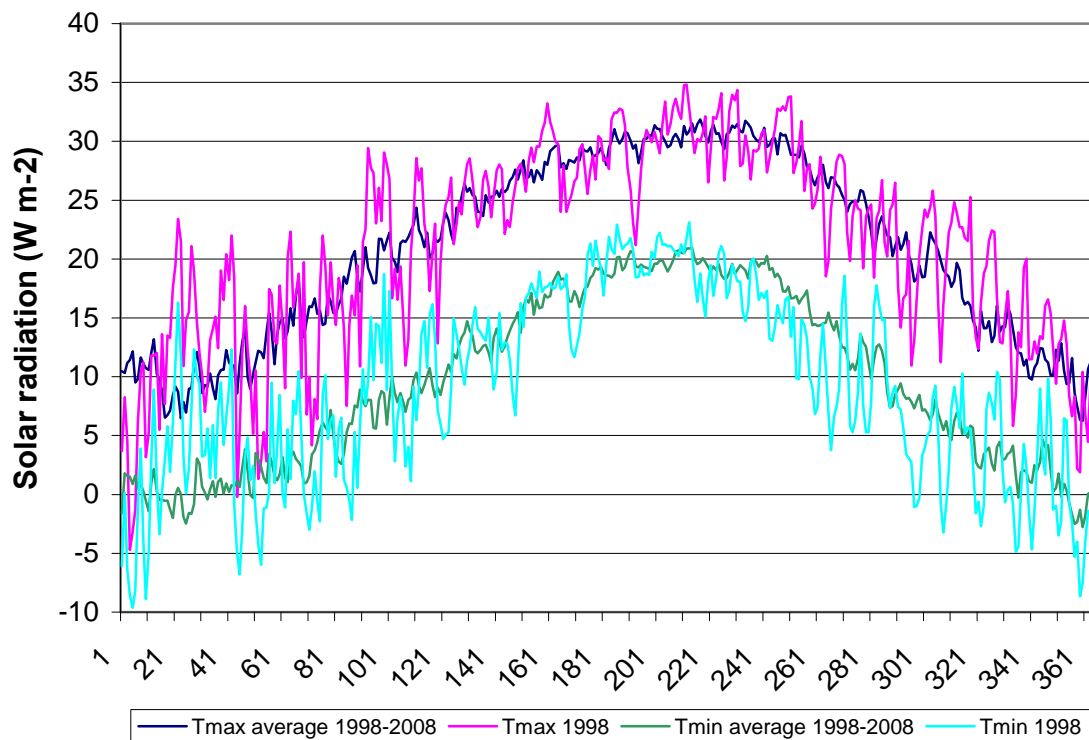


Figure 5 Daily maximum and minimum temperature at the Oak Ridge FACE site; Daily average values for the total time of weather records available for the Biome-BGC simulation (1998-2008) and daily values for the year 1999.

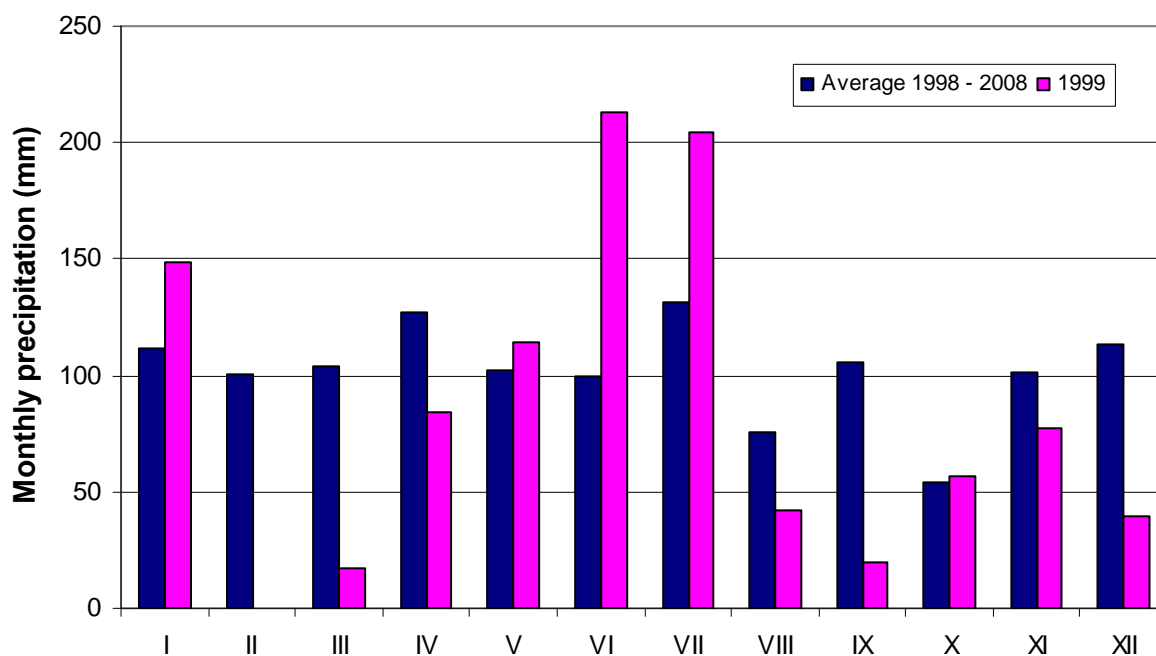
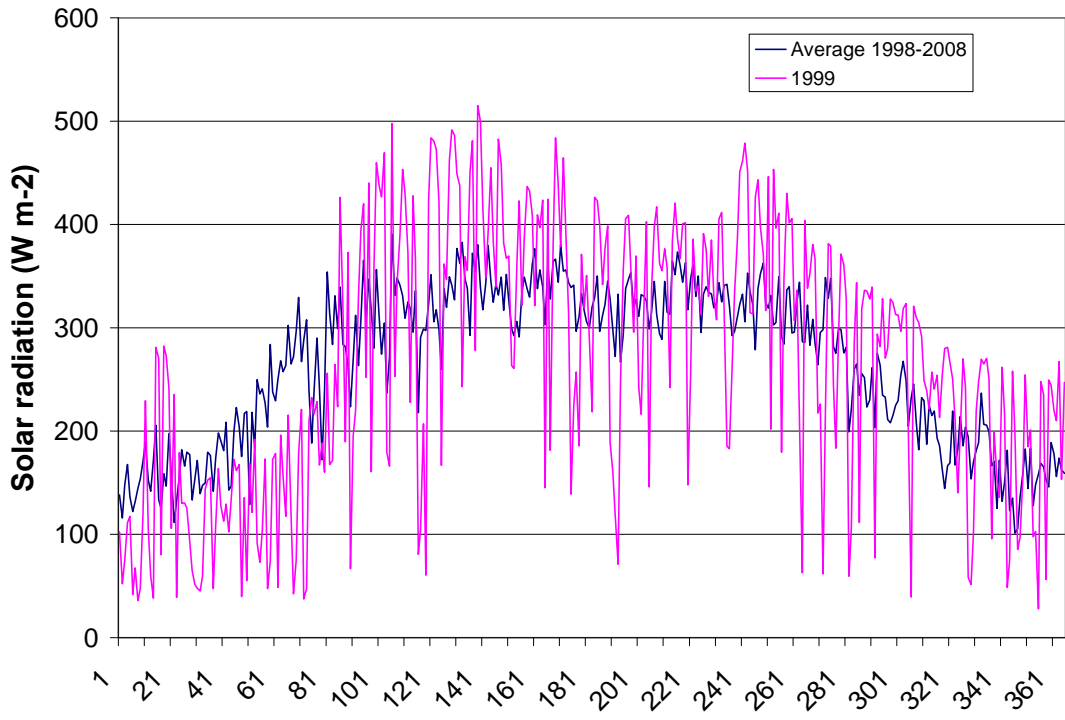
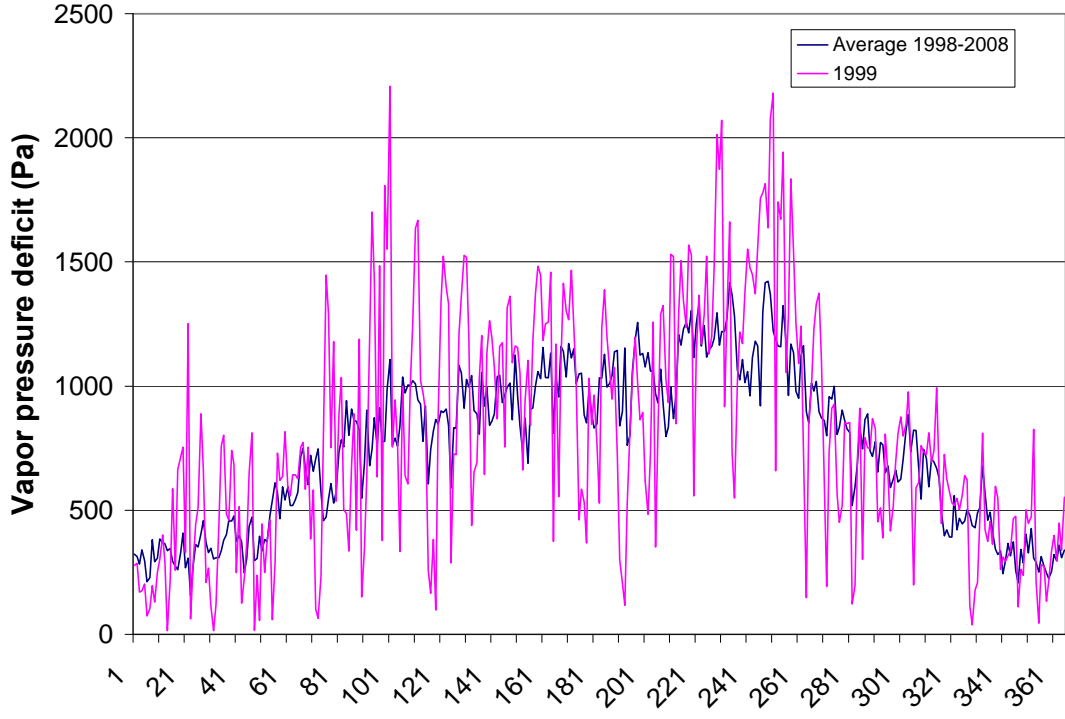


Figure 6 Monthly precipitation at the Oak Ridge FACE site; Monthly average values for the total time of weather records available for the Biome-BGC simulation (1998-2008) and monthly values for the year 1999.



**Figure 7** Daily incident solar radiation at the Oak Ridge FACE site; Daily average values for the total time of weather records available for the Biome-BGC simulation (1998-2008) and daily values for the year 1999.



**Figure 8** Vapor pressure deficit at the Oak Ridge FACE site; Daily average values for the total time of weather records available for the Biome-BGC simulation (1998-2008) and daily values for the year 1999.

## 3.2.2 Parameterization

### 3.2.2.1 Site constants and variables

The model needs a couple of site constants (Table 1) for the atmospheric pressure, the total shortwave radiation absorbed by the ecosystem and the soil water holding capacity. The albedo was set to 0.2, a typical value for the reflectance of broadleaved forests. The other parameters were known from measurements.

**Table 1 Site constants for the Biome-BGC simulations for the Oak Ridge FACE experiment**

Latitude (°)	Elevation (m a.s.l.)	Albedo	Effective soil depth (m)	Soil texture		
				Sand (%)	Silt (%)	Clay (%)
35.9	227	0.2	2.0	21	55	24

Nitrogen annually entering the ecosystem by atmospheric deposition was assumed to be  $0.0006 \text{ kg m}^{-2} \text{ y}^{-1}$ . In version of the model used for this study the nitrogen deposition usually gets scaled with the atmospheric  $\text{CO}_2$  concentration, also starting out from a low preindustrial value and increasing to the currently measured value. Since we are dealing with an experiment on elevated  $\text{CO}_2$  a scaling of nitrogen deposition with the atmospheric  $\text{CO}_2$  content was not possible. We had to choose a constant value that actually lies below the current nitrogen deposition value of  $12 \text{ kg m}^{-2} \text{ y}^{-1}$  in order to not enrich the ecosystem too much in nitrogen over the course of the whole simulation run.

The IS92a data set (Schimel et al. 1994) is used to describe the increase in atmospheric  $\text{CO}_2$  concentration since the industrial revolution. The first entry in this data set given for the year 1765 has the value of 278 ppm and is also used for the simulations of the years before.

### 3.2.2.2 Ecophysiological constants

Next to the site parameterization a vegetation specific parameterization is necessary. 42 ecophysiological parameters are required, which are stored in an ‘epc’-file (ecophysiological constants). Initially, parameter sets for three main forest vegetation types were published by White et al. (2000), i.e. evergreen needle leafed forests, deciduous needle leafed forests and deciduous broad leafed forests, together with three parameter sets for other plant functional types, i.e. shrub lands, C3 grass land and C4 grass land. A more forest type specific (Thornton et al. 2002) or even species specific (Pietsch et al. 2005) parameterization is possible and recommended for smaller scale studies. The required parameters, however, are mostly hard to measure and some can only be estimated from other data. For this study we could rely on an

unusually high number of different measurements done at the study site throughout the last couple of years. This facilitated a more site-specific parameterization than for most of the previous application cases of the Biome-BGC model. Concurrently, some shortcomings of the model's ability to picture nature become apparent, i.e. ecophysiological properties of the described vegetation types, which are addressed with single parameters, turn out to vary with the season or the stand age. The mechanisms underlying these shifts in ecophysiological characteristics are still elusive, though. They are complex and need to be investigated at smaller scales. In the future new findings can ideally be integrated into the model.

**Table 2 Epc (Ecophysiological-constants) -file for *Liquidambar styraciflua* grown under ambient CO<sub>2</sub> at the Oak Ridge FACE experiment.**

Li_sty_aCO <sub>2</sub>	( <i>Liquidambar styraciflua</i> under ambient CO <sub>2</sub> at ORNL FACE experiment)
1	(flag) 1 = WOODY 0 = NON-WOODY
0	(flag) 1 = EVERGREEN 0 = DECIDUOUS
1	(flag) 1 = C3 PSN 0 = C4 PSN
1	(flag) 1 = MODEL PHENOLOGY 0 = USER-SPECIFIED PHENOLOGY
0	*(yday) yearday to start new growth (when phenology flag = 0)
0	*(yday) yearday to end litterfall (when phenology flag = 0)
0.2	(prop.) transfer growth period as fraction of growing season (personal assessment)
0.3	(prop.) litterfall as fraction of growing season (personal assessment)
1	(1/yr) annual leaf and fine root turnover fraction (White et al. 2000)
0.7	(1/yr) annual live wood turnover fraction (White et al. 2000)
0.005	(1/yr) annual whole-plant minimum mortality fraction (personal assessment)
0.02	(1/yr) annual whole-plant maximum mortality fraction (personal assessment)
225	(yrs) length for (low) elliptic mortality (personal assessment)
75	(yrs) length for (high) elliptic mortality (personal assessment)
0	(1/yr) annual fire mortality fraction (ORNL)
0.38	(ratio) (ALLOCATION) new fineroot C : new leaf C (ORNL)
2.44	(ratio) (ALLOCATION) new stem C : new leaf C (ORNL)
0.16	(ratio) (ALLOCATION) new live wood C : new total wood C (White et al. 2000)
0.08	(ratio) (ALLOCATION) new coarseroot C : new stem C (ORNL)
0.1	(ratio) (ALLOCATION) current growth : storage growth (ORNL)
30	(kgC/kgN) C:N of leaves (ORNL)
58	(kgC/kgN) C:N of leaf litter (ORNL)
44	(kgC/kgN) C:N of fine roots (ORNL)
50	(kgC/kgN) C:N of live wood (White et al. 2000)
430	(kgC/kgN) C:N of dead wood (ORNL)
0.38	(DIM) leaf litter labile proportion (White et al. 2000)
0.44	(DIM) leaf litter cellulose proportion (White et al. 2000)
0.18	(DIM) leaf litter lignin proportion (White et al. 2000)
0.34	(DIM) fine root labile proportion (White et al. 2000)
0.44	(DIM) fine root cellulose proportion (White et al. 2000)
0.22	(DIM) fine root lignin proportion (White et al. 2000)
0.77	(DIM) dead wood cellulose proportion (White et al. 2000)
0.23	(DIM) dead wood lignin proportion (White et al. 2000)
0.005	(1/LAI/d) canopy water interception coefficient (personal communication with P. Thornton)
0.54	(DIM) canopy light extinction coefficient (White et al. 2000)
2	(DIM) all-sided to projected leaf area ratio (White et al. 2000)
25	(m <sup>2</sup> /kgC) canopy average specific leaf area (projected area basis) (ORNL)
1.26	(DIM) ratio of shaded SLA:sunlit SLA (ORNL)
0.12	(DIM) fraction of leaf N in Rubisco (personal communication with P. Thornton)
0.004	(m/s) maximum stomatal conductance (projected area basis) (personal assessment)
0.00006	(m/s) cuticular conductance (projected area basis) (White et al. 2000)
0.01	(m/s) boundary layer conductance (projected area basis) (White et al. 2000)
-0.334	(MPa) leaf water potential: start of conductance reduction (White et al. 2000)
-2.2	(MPa) leaf water potential: complete conductance reduction (White et al. 2000)
1100	(Pa) vapor pressure deficit: start of conductance reduction (White et al. 2000)
3600	(Pa) vapor pressure deficit: complete conductance reduction (White et al. 2000)
0	(°C) night temperature: start of conductance reduction (White et al. 2000)
-8	(°C) night temperature: complete of conductance reduction (White et al. 2000)

**Table 3 Epc (Ecophysiological-constants) -file for *Liquidambar styraciflua* grown under elevated CO<sub>2</sub> at the Oak Ridge FACE experiment.**

Li_sty_eCO <sub>2</sub>		(Liquidambar styraciflua under elevated CO <sub>2</sub> at ORNL FACE experiment)
1	(flag)	1 = WOODY            0 = NON-WOODY
0	(flag)	1 = EVERGREEN      0 = DECIDUOUS
1	(flag)	1 = C3 PSN           0 = C4 PSN
1	(flag)	1 = MODEL PHENOLOGY   0 = USER-SPECIFIED PHENOLOGY
0	*(yday)	yearday to start new growth (when phenology flag = 0)
0	*(yday)	yearday to end litterfall (when phenology flag = 0)
0.2	(prop.)	transfer growth period as fraction of growing season (personal assessment)
0.3	(prop.)	litterfall as fraction of growing season (personal assessment)
1	(1/yr)	annual leaf and fine root turnover fraction (White et al. 2000)
0.7	(1/yr)	annual live wood turnover fraction (White et al. 2000)
0.005	(1/yr)	annual whole-plant minimum mortality fraction (personal assessment)
0.02	(1/yr)	annual whole-plant maximum mortality fraction (personal assessment)
225	(yrs)	length for (low) elliptic mortality (personal assessment)
75	(yrs)	length for (high) elliptic mortality (personal assessment)
0	(1/yr)	annual fire mortality fraction (ORNL)
0.72	(ratio)	(ALLOCATION) new fineroot C : new leaf C (ORNL)
2.49	(ratio)	(ALLOCATION) new stem C : new leaf C (ORNL)
0.16	(ratio)	(ALLOCATION) new live wood C : new total wood C (White et al. 2000)
0.07	(ratio)	(ALLOCATION) new coarseroot C : new stem C (ORNL)
0.1	(ratio)	(ALLOCATION) current growth : storage growth (ORNL)
33	(kgC/kgN)	C:N of leaves (ORNL)
67	(kgC/kgN)	C:N of leaf litter (ORNL)
44	(kgC/kgN)	C:N of fine roots (ORNL)
50	(kgC/kgN)	C:N of live wood (White et al. 2000)
434	(kgC/kgN)	C:N of dead wood (ORNL)
0.38	(DIM)	leaf litter labile proportion (White et al. 2000)
0.44	(DIM)	leaf litter cellulose proportion (White et al. 2000)
0.18	(DIM)	leaf litter lignin proportion (White et al. 2000)
0.34	(DIM)	fine root labile proportion (White et al. 2000)
0.44	(DIM)	fine root cellulose proportion (White et al. 2000)
0.22	(DIM)	fine root lignin proportion (White et al. 2000)
0.77	(DIM)	dead wood cellulose proportion (White et al. 2000)
0.23	(DIM)	dead wood lignin proportion (White et al. 2000)
0.005	(1/LAI/d)	canopy water interception coefficient (personal communication with P. Thornton)
0.54	(DIM)	canopy light extinction coefficient (White et al. 2000)
2	(DIM)	all-sided to projected leaf area ratio (White et al. 2000)
23.6	(m <sup>2</sup> /kgC)	canopy average specific leaf area (projected area basis) (ORNL)
1.26	(DIM)	ratio of shaded SLA:sunlit SLA (ORNL)
0.12	(DIM)	fraction of leaf N in Rubisco (personal communication with P. Thornton)
0.0035	(m/s)	maximum stomatal conductance (projected area basis) (personal assessment)
0.00006	(m/s)	cuticular conductance (projected area basis) (White et al. 2000)
0.01	(m/s)	boundary layer conductance (projected area basis) (White et al. 2000)
-0.334	(MPa)	leaf water potential: start of conductance reduction (White et al. 2000)
-2.2	(MPa)	leaf water potential: complete conductance reduction (White et al. 2000)
1100	(Pa)	vapor pressure deficit: start of conductance reduction (White et al. 2000)
3600	(Pa)	vapor pressure deficit: complete conductance reduction (White et al. 2000)
0	(°C)	night temperature: start of conductance reduction (White et al. 2000)
-8	(°C)	night temperature: complete of conductance reduction (White et al. 2000)

### **3.2.2.2.1 Transfer growth period**

The transfer growth period in the model is the time in spring when carbon that was stored during the last growing season is deployed to allow first plant growth. In the model the number of days with growth from the carbon transfer pool is calculated as a fraction of the growing season. This value was commonly set to 0.2 for this study. No direct measurements to verify this value had been done. And in reality such a strictly defined transfer growth period probably doesn't even exist. I got a hint of a reasonable value from comparing the measured and simulated LAI trajectory at the beginning of the growing season. I chose the value where the shape of the two curves matched the best.

### **3.2.2.2.2 Litter fall as a fraction of growing season**

During the litterfall period leaf biomass is assigned to the litter pool. Since litter has a higher C/N ratio than leaves (see chapter 3.2.2.2.6) not all nitrogen from the leaf pool is moved to the litter pool. It gets assigned to a nitrogen retranslocation pool from which a part of next years nitrogen demand for growth can be drawn.

The litterfall period, like the transfer growth period, is given as a fraction of the growing season. Similar to the transfer growth period, I derived a reasonable value from the measured LAI curve. For both treatments I chose the value of 0.3.

### **3.2.2.2.3 Annual turnover fractions**

a) Leaf and fine root turnover:

The modeled species *Liquidambar styraciflua* is a deciduous tree. The annual turnover fraction for leaves therefore is 1.0. White et al. (2000) set the fine root turnover fraction to the same value. In this way it is also used in the Biome-BGC model.

b) Life wood turnover fraction:

This value was set to 0.7, the value given in White et al. (2000) for all woody biomes trees.

### **3.2.2.2.4 Plant mortality**

During the spin-up run a dynamic mortality routine was used, whereas for the subsequent simulation years the mortality was set to a constant value. For lack of information on the life cycle characteristics of a pure *Liquidambar styraciflua* forest the minimum and maximum annual mortality rate, as well as the length of the low and the high elliptic mortality had to be estimated. Minimum mortality was set to 0.5%, maximum mortality to 2% and the length of the low and high elliptic mortality to 225 and 75 years, respectively. As constant mortality the



value of 0.5% was taken again. It is assumed that management (simulated after the spin-up run) keeps the mortality low.

No difference in plant mortality rates between the forests grown at ambient and elevated atmospheric CO<sub>2</sub> was assumed.

### 3.2.2.2.5 Carbon and nitrogen allocation

The allocation of carbon and nitrogen available for growth is based on allometric parameters that relate carbon allocation between various plant compartments (see Table 4).

**Table 4 Allocation parameters for woody species**

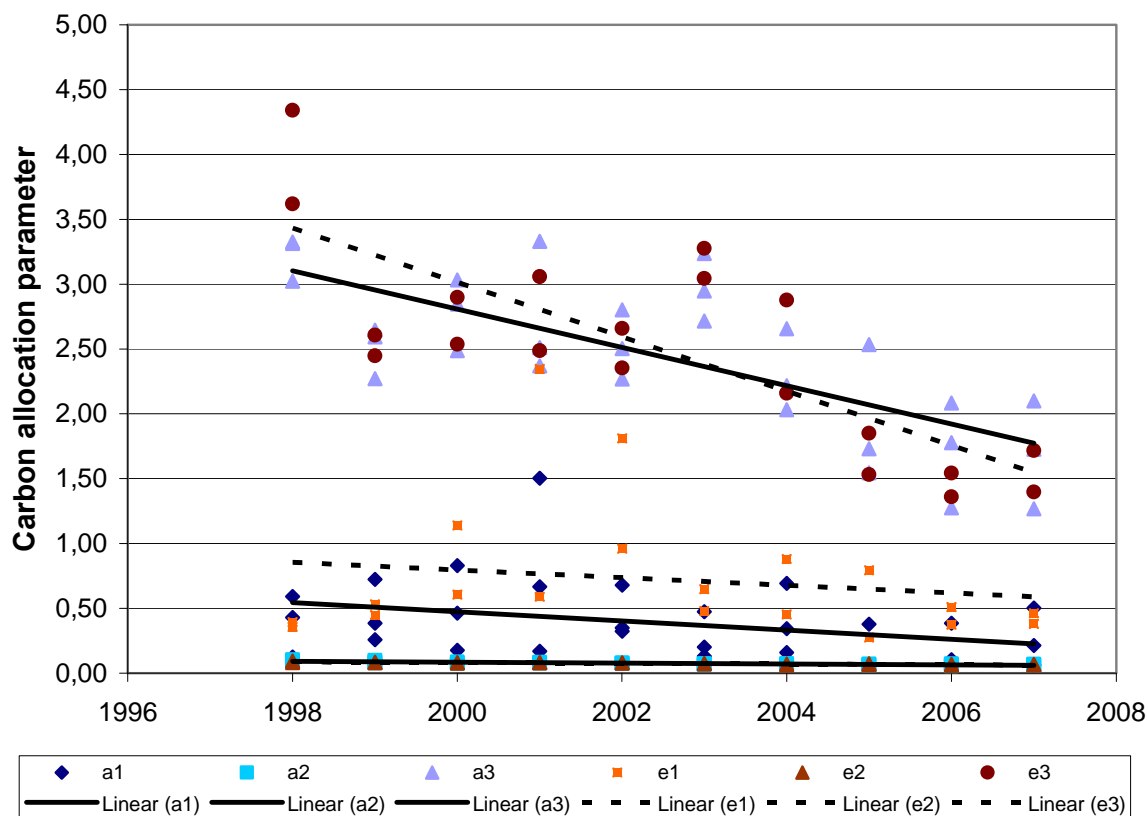
	<b>Ambient CO<sub>2</sub> treatment</b>	<b>Elevated CO<sub>2</sub> treatment</b>
<b>ratio of new fine root C to new leaf C</b>	a1	e1
<b>ratio of new coarse root C to new stem C</b>	a2	e2
<b>ratio of new stem C to new leaf C</b>	a3	e3
<b>ratio of new live wood C to new total wood C</b>	a4	e4

Parameters a1-a3 and e1-e3 were derived from annual NPP calculations for the different plant compartments done at the Oak Ridge FACE site. The procedure was already briefly described in paragraph 3.1.2. NPP was given as the weight of dry biomass per unit land area per year. This had to be converted into gram carbon per square meter per year. Carbon content of leaves, fine roots and wood was given by Norby et al. (2002) (see Table 5) so NPP of biomass could be easily converted into NPP carbon.

**Table 5 Carbon content of different plant compartments in percent of dry biomass for Liquidambar styraciflua grown at the Oak Ridge FACE site. Source: Norby et al. (2002)**

<b>Foliage [C] (%)</b>	<b>Fine root [C] (%)</b>	<b>Wood [C] (%)</b>
<b>46.3</b>	39.6	47.1

For each plant compartment and for each year from 1998 – 2007 the average over the plots of the same treatment was calculated. Statistically significant trends exist for the ratio of new coarse root C to new stem C (a2, e2) and the ratio of new stem C to new leaf C (a3, e3) for both treatments (see Figure 9). The model does not allow changing allocation parameters over the years, though. To find algorithms to describe these shifts in allocation will be an important research field in the future. Since this study focused more on the water budget, we decided on simply taking the overall average for the parameters a1-a3 and e1-e3 (see Table 6).



**Figure 9 Carbon allocation parameters for American Sweetgum at the Oak Ridge FACE site: a1 and e1: ratio of new fineroot C to new leaf C, a2 and e2: ratio of new coarseroot C to new stem C and a3 and e3: ratio of new stem C to new leaf C for ambient CO<sub>2</sub> treatments and elevated CO<sub>2</sub> treatments, respectively.**

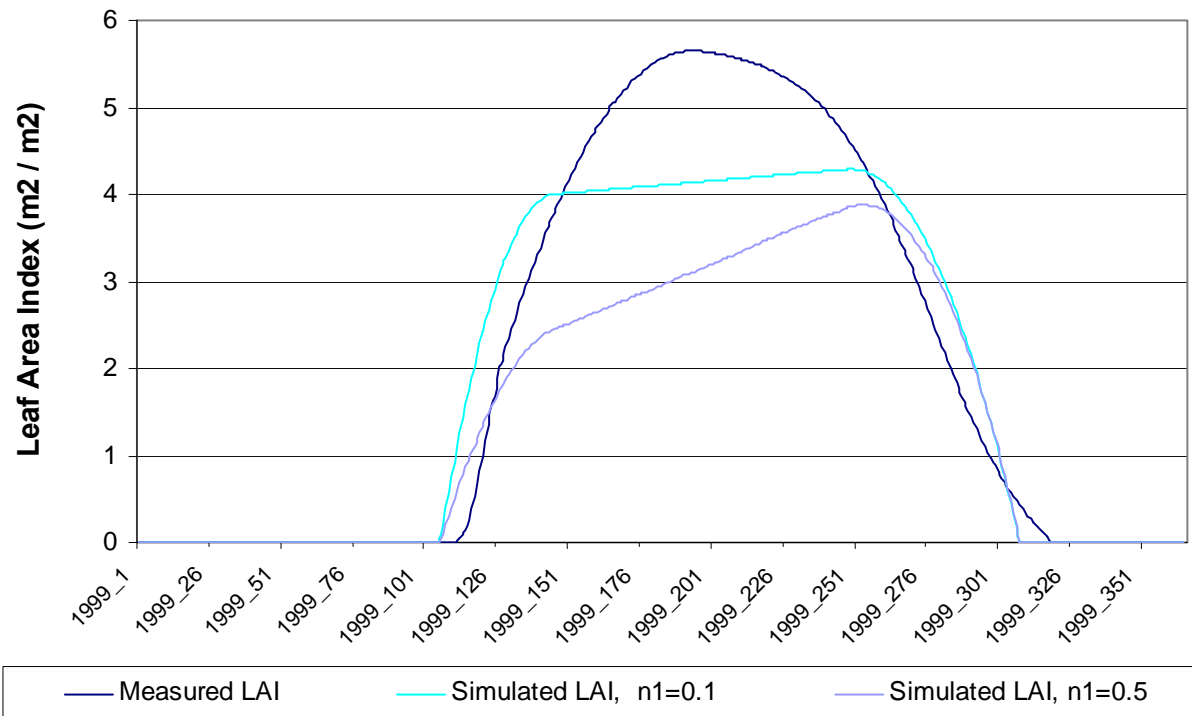
For the parameters a4 and e4 giving the ratio of new live wood C to new total wood C we used the value of 0.16 for deciduous broadleaved forests given in White et al. (2000) for there weren't any measurements available (see Table 6).

**Table 6 Carbon allocation parameters for *Liquidambar styraciflua* for ambient and elevated atmospheric CO<sub>2</sub> treatments**

	new fineroot C : new leaf C	new coarseroot C : new stem C	new stem C : new leaf C	new live wood C : new total wood C
<b>Ambient</b>	0.38	0.08	2.44	0.16
<b>Elevated</b>	0.72	0.07	2.49	0.16

Two additional parameters are necessary for the allocation calculations. The ratio of growth respiration C to new growth C (g1) is set to 0.3 for all plant functional types (Thornton et al., 2002), based values given for construction costs of different woody and non-woody tissues given by Larcher (1995). The allocation ratio of available carbon or nitrogen for this year's

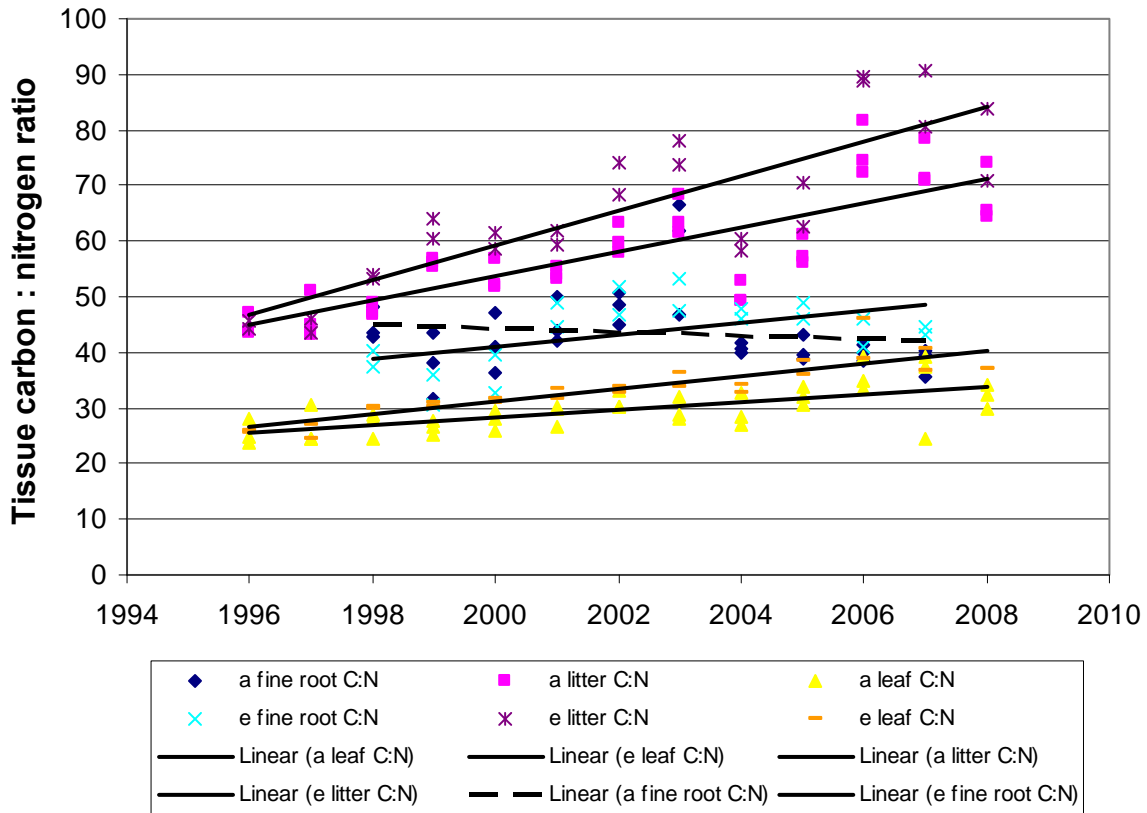
growth to next year's growth (storage growth) ( $n_1$ ) was set to 0.1. No direct measurements to derive and/or justify this value were available but choosing this value instead of e.g. 0.5 gave a more suitable shape of the LAI-curve (LAI vs. day of the year) (compare Figure 10).



**Figure 10 Measured Leaf Area Index (LAI) of *Liquidambar styraciflua* at a plot of the Oak Ridge FACE site ambient CO<sub>2</sub> treatment and simulated LAI with the parameter  $n_1$  (ratio of new available carbon used for current growth to carbon allocated to a storage pool for growth in the next year) set to 0.5 (test) and 0.1 (later used).**

### 3.2.2.2.6 C/N ratios

Carbon to nitrogen ratios for all plant tissues are used to determine the nitrogen content of these tissues and to infer the maintenance respiration – a function of the tissue nitrogen content – and in case of leaves, to determine the temperature dependent maximum rate of carboxylation ( $V_{cmax}$ ). Biomass and nitrogen content of the relevant plant organs had been measured annually (Norby et al. 2008a, Norby et al. 2008b). From those data and the known fractions of carbon in the various plant compartments (see also paragraph 3.2.2.2.5; Norby et al., 2002) the different C/N ratios could easily be derived (see Figure 11).



**Figure 11 Carbon to nitrogen ratios for different plant tissues (kg C / kg N) of *Liquidambar styraciflua* for ambient and elevated CO<sub>2</sub> treatments at the Oak Ridge FACE experiment.**

The carbon to nitrogen ratios of most tissues show a positive trend over the years. The only exemption is the fine root C/N for the ambient CO<sub>2</sub> treatment. Like for the allocation ratios (see previous chapter) dynamics of C/N ratios are not considered in the current model version. Therefore, the mean values over the whole observation period were chosen for the model parameterization (see Table 6).

**Table 7 Carbon to nitrogen ratios for different plant tissues (kg C / kg N) of *Liquidambar styraciflua* at the Oak Ridge FACE site**

	C:N of leaves	C:N of leaf litter	C:N of fine roots	C:N of live wood	C:N of dead wood
<b>Ambient</b>	30	58	44	50	430
<b>Elevated</b>	33	67	44	50	434

The carbon to nitrogen ratios of leaves and leaf litter tell us that approximately 50% of the leaf nitrogen are taken up by the plant before leaf abscission. In the model this nitrogen and

nitrogen originating from dying live wood parts (consider the difference in C/N of live wood and dead wood!) is kept in a storage or also termed retranslocation pool until this pool is permitted to be depleted during the following year's growth.

#### ***3.2.2.2.7 Carbon compounds composition of different plant parts***

For leaves, litter and wood the fraction of carbon in labile compounds (soluble in hot water or alcohol), in celluloses (soluble in acid) and in lignin (not soluble in acid) need to be known. No labile carbon is assumed to be contained in wood. The different compounds show different degradation properties, i.e. the labile pool has the highest mineralization coefficient and the lignin is the most recalcitrant compound with the lowest mineralization coefficient. Values specific for *Liquidambar styraciflua* were not available, therefore the standard parameterization for deciduous broadleaved trees of White et al. (2000) was used.

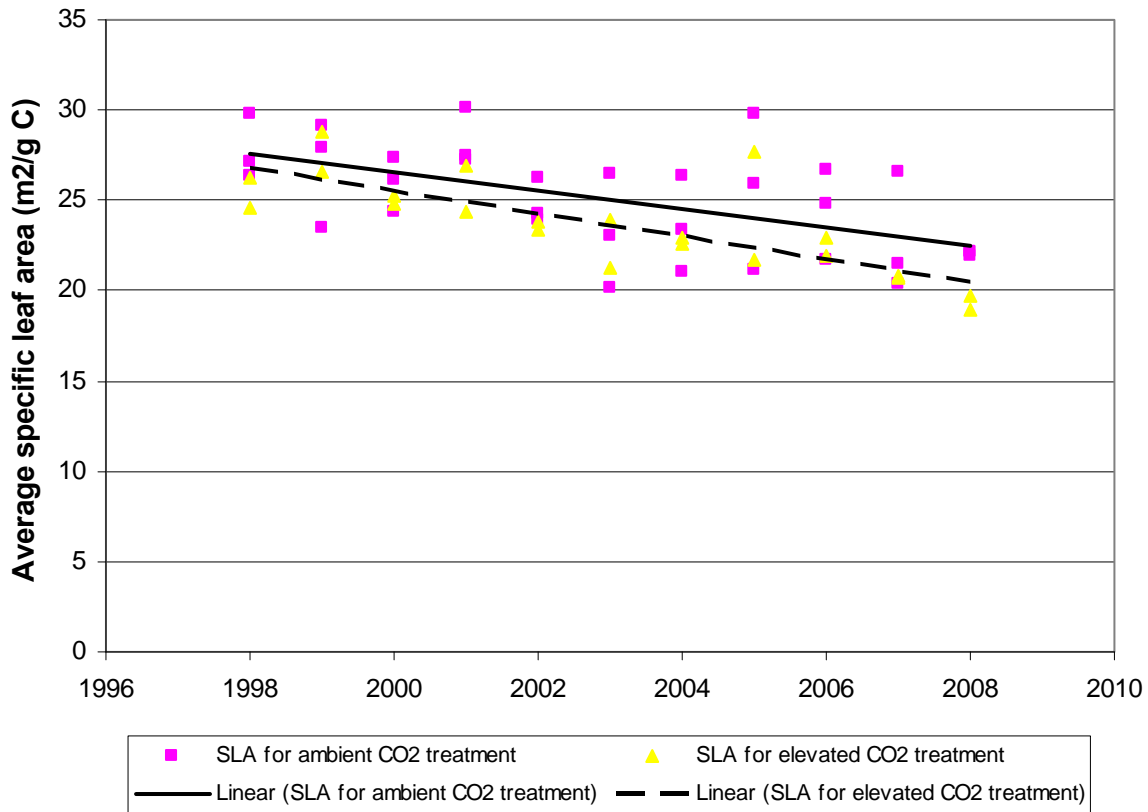
#### ***3.2.2.2.8 Canopy interception coefficients***

The calculation of rainfall interception uses a water interception coefficient that is scaled with the precipitation intensity and the one-sided leaf area index to yield the total canopy intercepted water. According to P. Thornton values used in previous studies were often too high and he therefore suggested a canopy water interception coefficient of 0.005.

The canopy light extinction coefficient was taken from the ecophysiological parameter set for deciduous broadleaved forest of White et al. (2000).

#### ***3.2.2.2.9 Leaf morphological and physiological characteristics***

As for broadleaved species usual, the ratio of all-sided to projected leaf area was set to 2.0 (White et al., 2000). The canopy average specific leaf area (SLA) was derived from available canopy average leaf mass per area (LMA) data for the different plots, treatments and years (Norby and Iversen, 2006). LMA values were multiplied with the carbon content of leaves (see Table 5), then the inverse was taken to get the SLA and finally the SLA values were averaged per treatment over all plots and years. Although a negative trend over the years for both treatments exists (see Figure 12) it was necessary to get a single value because the current model version does not treat dynamics in the SLA.



**Figure 12 Specific leaf area (SLA) (average among the plots of the same treatment) for ambient and elevated CO<sub>2</sub> treatments at the Oak Ridge FACE experiment.**

In addition, the ratio of shaded to sunlit leaves SLA was calculated from two years (1999 and 2009) of LMA measurements in one meter steps over the whole canopy depth. The LMA was weighted by the LAI at a certain canopy depth and the top two measurements were used to get the average sunlit LMA and the rest to derive the average shaded LMA. The LMA was again converted into the SLA as described above and the ratio between shaded SLA and sunlit SLA was calculated for both CO<sub>2</sub> treatments.

### 3.2.2.2.10 Conductance parameters

As described earlier, total leaf level conductance follows the electrical circuit analogy of Nobel (1991), with stomatal and cuticular conductance in parallel and leaf boundary layer conductance in series. Boundary layer and cuticular conductance are taken from the parameterization of White et al. (2000) for deciduous broadleaved forests. A maximum stomatal conductance was estimated from a variety of earlier stomatal conductance measurements (Gunderson et al., 2002; Wullschleger et al., 2002) needs maybe also more explanation). Maximum stomatal conductance for trees grown under ambient atmospheric

CO<sub>2</sub> was set to 0.004 m s<sup>-1</sup>, whereas for the elevated CO<sub>2</sub> treatment a lower value, 0.0035 m s<sup>-1</sup> was used. This is in accordance with observations by Gunderson et al. (2002) that the difference in stomatal conductance between ambient and elevated CO<sub>2</sub> treatments is higher for situations with a sufficiently moist soil and a low vapour pressure deficit and that the difference diminishes with a stress induced stomata closure. The start and end values for linear reductions of the maximum stomatal conductance induced by low leaf water potential, high VPD and low night time temperatures are the same as in deciduous broadleaved parameterization of White et al. (2000).

### 3.2.2.3 Parameter changes in the code

#### 3.2.2.3.1 Soil water retention-curve

The daily calculation of the soil water potential serves the estimation of the stomatal conductivity. The soil water potential is determined from the soil water potential at saturation,  $\Psi_{sat}$ , the volumetric water content at saturation,  $\theta_{sat}$  and an empirical shape parameter, the Clapp-Hornberger constant b (Cosby et al. 1984). These soil properties are calculated from the texture or particle size distribution. The texture is the volume-percentage of sand (2-0.05mm), silt (0.05-0.002mm) and clay (<0.002mm). The original procedure to calculate the soil water potential  $\Psi$  was slightly modified in order to describe a volumetric water content – soil water potential relationship fitting to a soil water retention curve previously determined at the Oak Ridge FACE site (see Equation 1 – 5 and Figure 13).

$$\Psi = \Psi_{sat} * \left( \frac{\theta}{\theta_{sat}} \right)^b$$

#### Equation 1 Soil water potential

$$\Psi_{sat} = -e^{(1.54 - 0.0095 * [\text{sand}] + 0.0063 * [\text{silt}] * \log(10)) * 9.8 * E - 5}$$

#### Equation 2 Saturated soil water potential

... where [Sand] and [Silt] are the volume-percentages of sand (2-0.05mm) and silt (0.05-0.002mm) respectively.

$$\text{a) } \theta_{sat} = \frac{50.5 - 0.142 * [Sand] - 0.037 * [Clay]}{100}$$

$$\text{b) } \theta_{sat} = \frac{45.5 - 0.142 * [Sand] - 0.037 * [Clay]}{100}$$

**Equation 3 Volumetric water content at saturation, (a) as usually calculated in the Biome-BGC model, (b) changed for the Oak Ridge FACE site.**

... where [Clay] is the volume-percentage of clay (<0.002mm).

$$\theta = \frac{W}{1000 * \text{effSd}}$$

**Equation 4 Volumetric water content**

... where W is the water content (kg/m<sup>2</sup>), effSd is the effective soil depth (soil depth decreased by fraction of stones >2mm, m) at the simulated site.

$$\text{a) } b = -(3.10 + 0.157 * [\text{clay}] - 0.003 * [\text{sand}])$$

$$\text{b) } b = -(1.90 + 0.157 * [\text{clay}] - 0.003 * [\text{sand}])$$

**Equation 5 Clapp-Hornberger parameter, (a) as usually calculated in the Biome-BGC model, (b) changed for the Oak Ridge FACE site.**



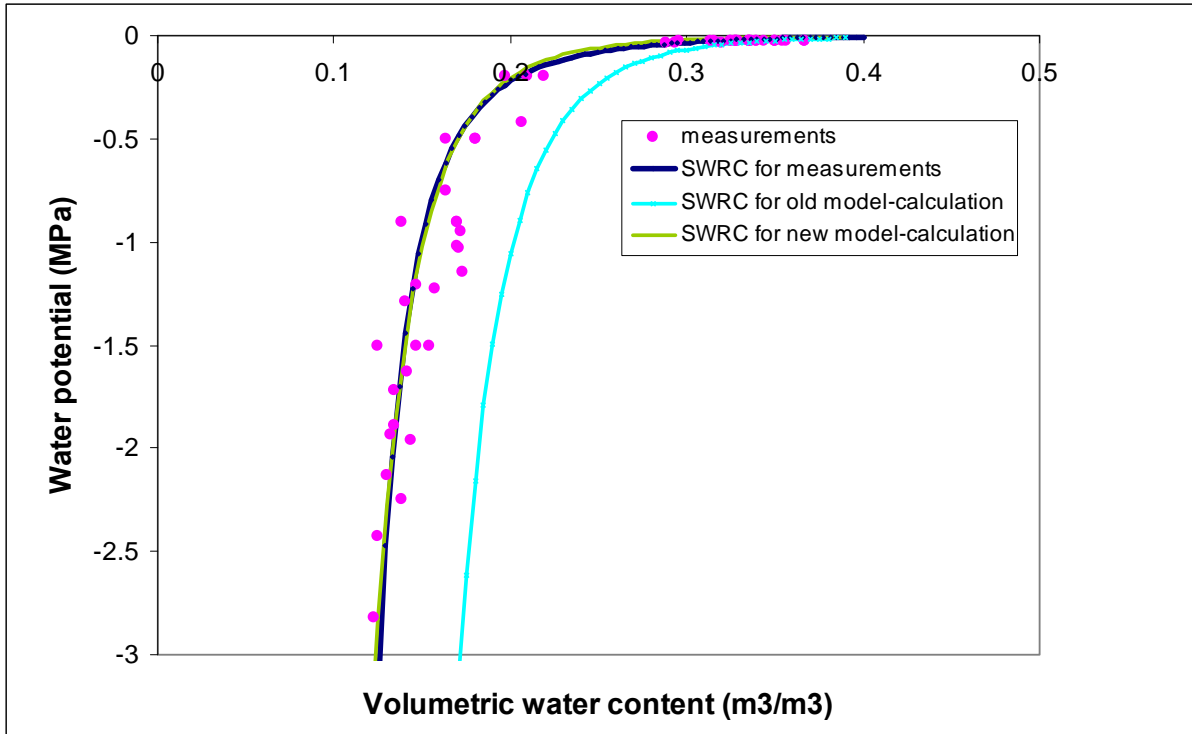


Figure 13 Soil water retention curves (SWRC): curve fitted to measurement data at the Oak Ridge FACE site and curves derived from the original (old) and the to the FACE site conditions adjusted (new) soil water potential calculation as implemented in the Biome-BGC model.

### 3.2.2.3.2 Phenology

The start of the leaf onset period is calculated with the empirical formulation of White (1997). A critical temperature sum ( $T_{critsum}$ ) must be reached to induce leaf flushing. It is usually calculated as in Equation 6a. However, for the Oak Ridge site an adjustment was done (Equation 6b).

$$a) T_{critsum} = e^{(4.795+0.129*T_{avg\_mean})}$$

$$b) T_{critsum} = e^{(5.07+0.129*T_{avg\_mean})}$$

**Equation 6 Critical soil temperature sum at which start of growing season is simulated. a) The equation after White (1997) as normally used in the Biome-BGC model and b) the equation as adjusted for the Oak Ridge FACE site.**

For the equations,  $T_{avg\_mean}$  is calculated as mean of the  $T_{avg}$  values of the total meteorological time series.  $T_{avg}$  itself is calculated as in Equation 7.

$$T_{avg} = \frac{T_{max} - T_{min}}{2}$$

Equation 7 Average daily temperature derived from daily maximum and minimum temperature.

The adjustment of the critical soil temperature sum calculation followed the comparison of the simulated day of the year when the LAI exceeded 0.5 for the first time with observations at the FACE site (see Figure 14). Between CO<sub>2</sub> enriched plots and the control plots no clear difference for the start of the vegetation period could be detected. For both treatments the same altered equation was henceforth used.

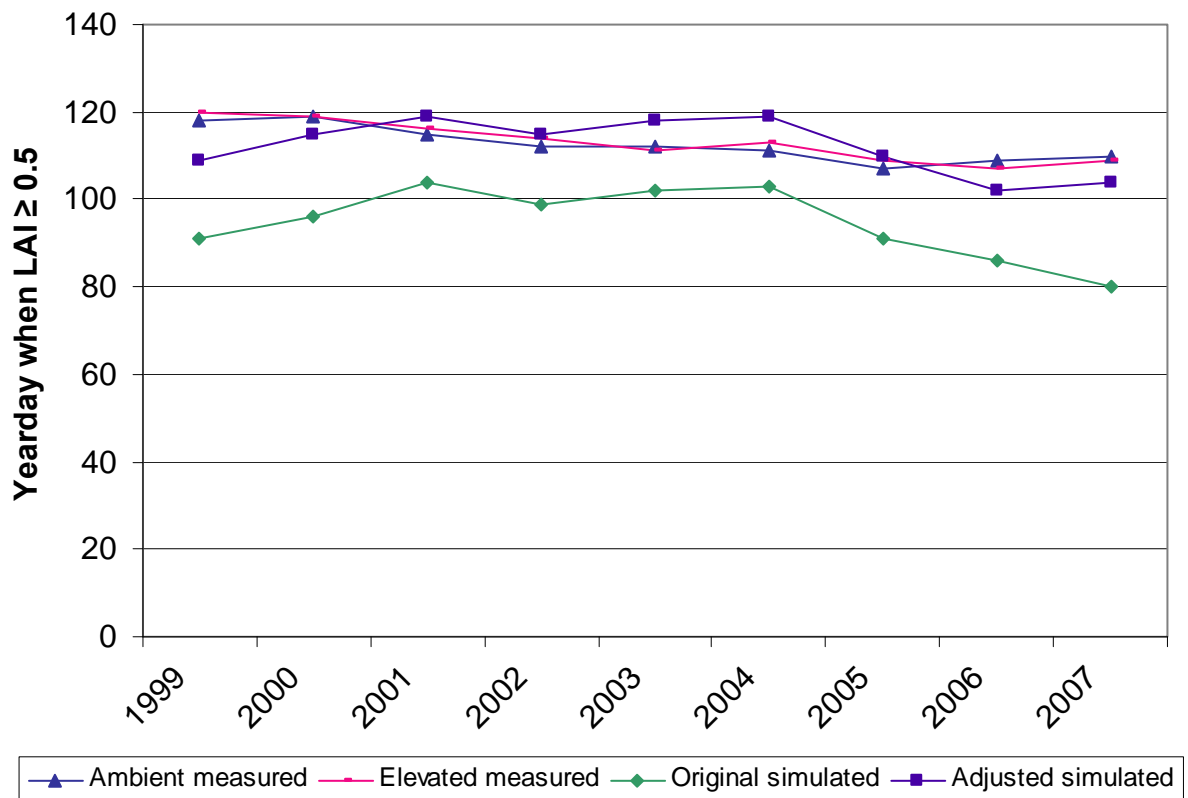


Figure 14 Yearday when the LAI exceeds 0.5 for the first time, given as a yearly mean for the CO<sub>2</sub> enriched and the control plots at the Oak Ridge FACE site and as simulated with the Biome-BGC model using the empirical phenology treatment of White (1997) (Original simulated) and the slightly altered formulation (Adjusted simulated).

### 3.2.3 Simulations

Having compiled the necessary model drivers, i.e. set of daily weather data for the years 1998-2008, and holding the ecophysiological parameterization for an under ambient CO<sub>2</sub> grown *Liquidambar styraciflua* forest and a CO<sub>2</sub> treated forest of the same species in hands, the next step is to perform the model self initialization run to bring the simulated forest ecosystem in a dynamic equilibrium with the prevailing climate and the physical and chemical site conditions. For this spin-up run the elliptic mortality routine as described earlier was used, and no difference whatsoever was made between plots later to become the elevated CO<sub>2</sub> treatment or the reference plots. In this set-up it took the forests 3700 simulation years to arrive at this dynamic equilibrium. Right afterwards land degradation (nutrient and soil carbon loss) caused by the transformation of the virgin forests into managed ecosystems needed to be represented in the model. For both plots a first clearcut and planting was therefore simulated in the first half of the 19<sup>th</sup> century and subsequently two more rotations were assumed until in 1987 the current stands were established. This is only a very rough approximation to the actual site history, which is only known in more or less detail for the 20<sup>th</sup> century. In fact, from 1943 to 1988 there was grassland at the site of the later plantation, and before 1943 the land was probably managed as a cornfield, for how long is not known. Unfortunately, the current model set up using a graphical user interface did not allow the simulation of this specific site history, although in general grassland (C3 and C4) could be simulated with the Biome-BGC model. For future simulations, when the focus will lie on the carbon cycle a more precise representation of the land-use history will be indispensable.

At the Oak Ridge FACE site the forest was actually planted in 1988, but one year old saplings were used. Consequently, simulated planting needed to be assumed one year earlier. From planting till the termination of the simulation with the end of 2008 the model was forced to run with the two different Sweetgum ecophysiological parameterizations. Ideally, for the first few years till the time when the CO<sub>2</sub> fumigation was switched on the parameterization still should have been identical. However, a switch of the epc-file is solely possible at a clearcut/planting intervention, which under normal conditions makes of course perfect sense. The output for selected model variables for the final two simulated forest stands was stored and prepared for analysis and for some comparisons with observations.

## 4 Results and discussion

### 4.1 Carbon budget

#### 4.1.1 Productivity

The Biome-BGC model gives a wide range of growth related output variables. For this report I decided to mainly talk about gross and net primary production for they are some of the most well known ecosystem variables.

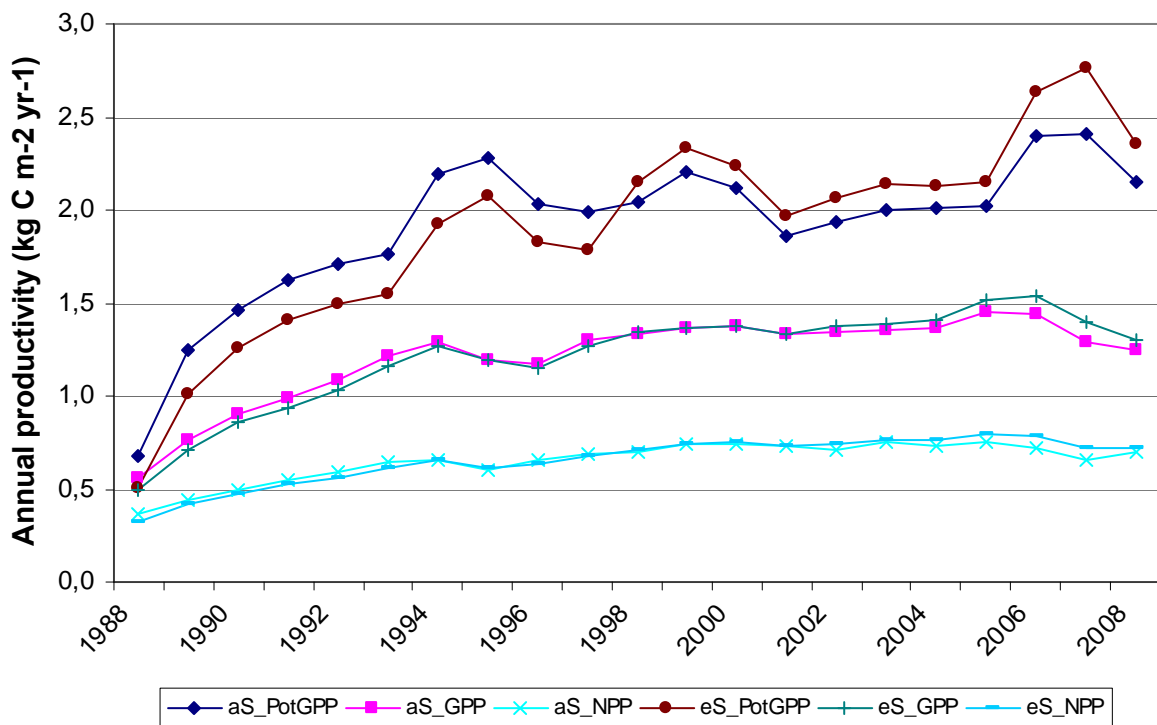
Annual growth may be expressed as annual net primary production NPP, since the NPP ( $\text{kg C m}^{-2} \text{ yr}^{-1}$ ) gives the amount of photosynthetically fixed carbon what is available for allocation to different plant organs for their construction. One limitation of this interpretation is, however, that a part of this carbon is stored for next year's growth. Consequently, NPP is not directly comparable with the sum of measured increment of the different plant compartments. The measured increment would rather compare with the sum of increases in the pool sizes of the simulated plant organs. This increment analysis was not part of the study, though. A comparison of simulated ambient and elevated  $\text{CO}_2$  treatment plots could be more easily done and was more in the focus of interest since this were the first elevated  $\text{CO}_2$  simulations done and the mere model response was not clear.

For the ambient and elevated  $\text{CO}_2$  treatment GPP and NPP steeply increased during the first couple of years since the stand had been established and then this increase flattens off (see Figure 15). This represents well the natural development of a forest stand where saplings can grow fast at the beginning when competition for light and nutrients is still low and later, with crown closure, competition markedly sets in.

The comparison of predicted ambient and elevated  $\text{CO}_2$  NPP gave only little differences between the treatments. This came rather unexpectedly and it was, frankly speaking, also disappointing. A second look at the data revealed that the plot with the ambient  $\text{CO}_2$  epc-file (ecophysiological parameterization) grew even better than the other plot during the first ten years, before the  $\text{CO}_2$  treatment commenced. Later, the elevated  $\text{CO}_2$  treatment plot could narrowly surpass the ambient  $\text{CO}_2$  treatment plot. The comparison of the gross primary production (GPP) values showed a similar picture. We may explain the rather poor performance of the simulated elevated  $\text{CO}_2$  plot by the reduced carbon allocation to the canopy. This growth pattern was caused by a parameterization resulting from the observed strong increase in root growth, but similar growth of the other plant compartments. Since the

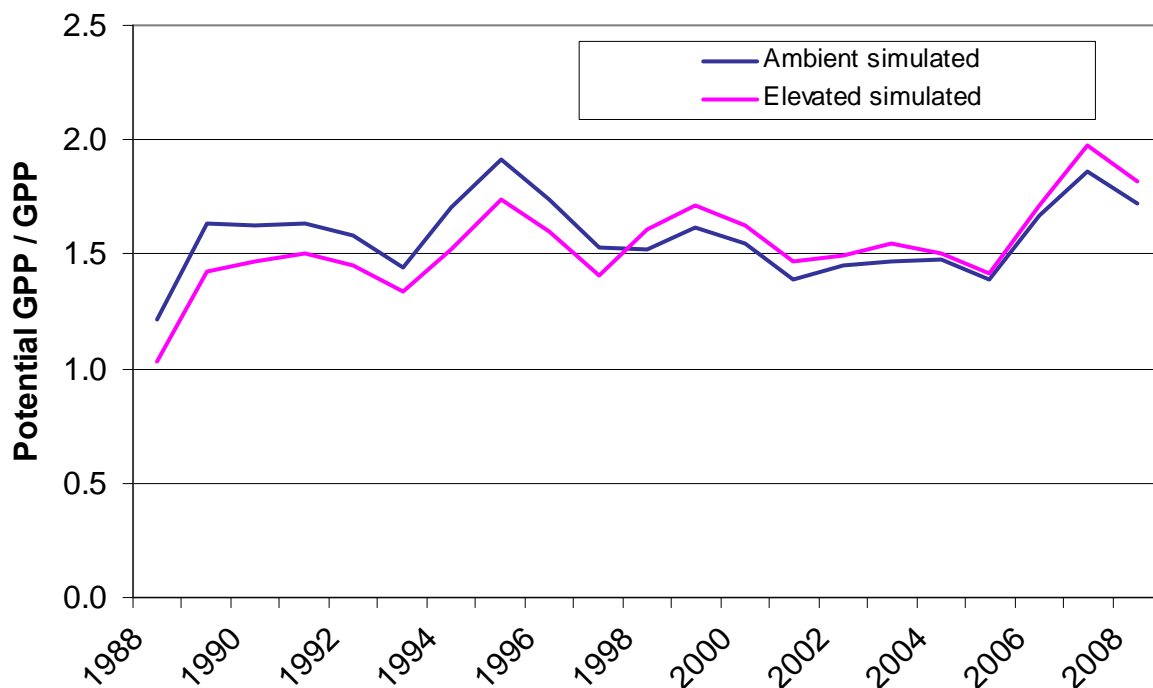
allocation ratio of fine root carbon to leaf carbon had to be set to about the double value for the elevated in comparison to the ambient CO<sub>2</sub> plot, relatively less carbon went into the canopy compartment. This reduced potential photosynthesis. In the natural ecosystem the fostered allocation of carbon into the root-biomass might have the benefit of better access to water or nitrogen as potentially limiting resources. In the model, however, no benefit whatsoever arises for the plant from this stronger root growth. This clearly has to be marked as an issue for future discussions for model improvement.

Net primary production is gross primary production minus growth and maintenance respiration, where growth respiration is a fixed percentage of carbon available for allocation and maintenance respiration depends on the nitrogen content of the respiring tissue and the temperature. For the two different treatments a divergence of the differences of GPP and NPP (not shown) might be anticipated from the different allocation patterns (elevated CO<sub>2</sub> plots have approximately the double fine root growth!) together with changed C/N ratios and total different growth. Still, NPP and GPP curves show similar shapes for both treatments (see Figure 15).



**Figure 15 Annual potential gross primary production (PotGPP) and actual productivity (GPP, net primary production NPP) simulated for the ambient (aS) and the elevated (eS) CO<sub>2</sub> treatment plots at the Oak Ridge FACE site from 1988, the year after planting, to 2008.**

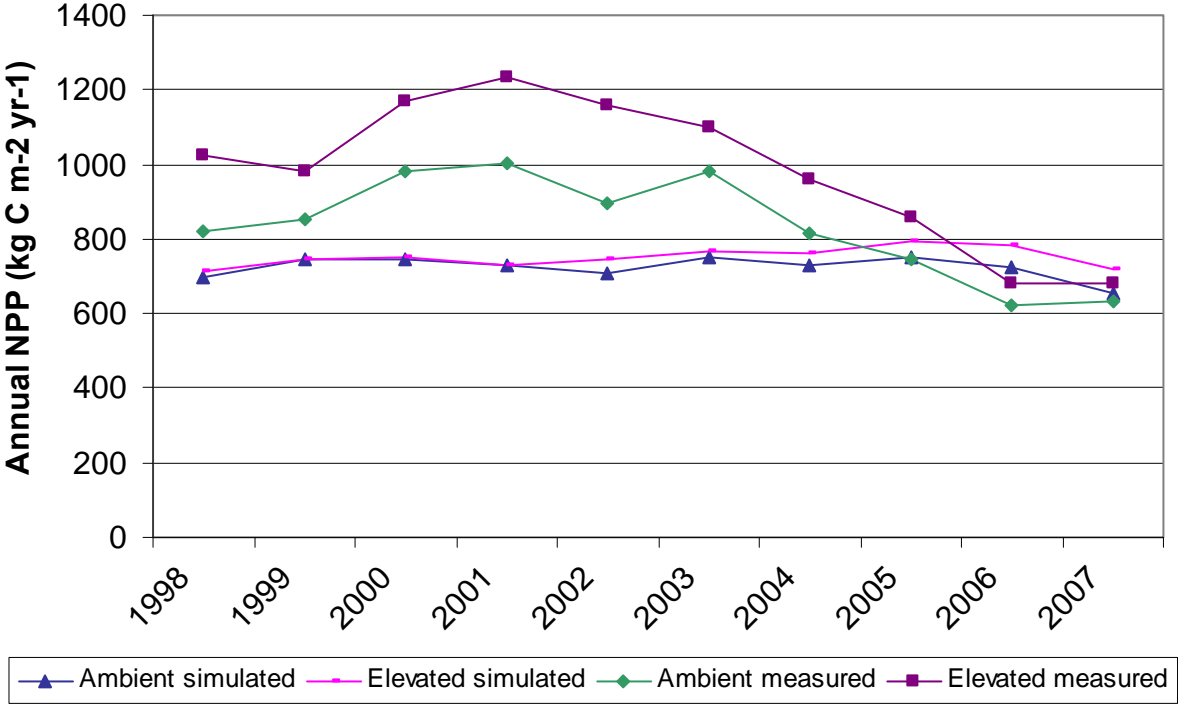
In the model, growth is limited by the mineral nitrogen availability from the soil. A reason for the low growth acceleration with the addition of CO<sub>2</sub> possibly is a shortage of nitrogen in the forest ecosystem. We can get an idea of the severeness of such a possible nitrogen limitation by investigating the potential GPP, another model output variable. It gives the GPP, which the simulated forest could have had if no nitrogen limitation had existed. For the first ten years, before the CO<sub>2</sub> experiment started, potential GPP for the elevated CO<sub>2</sub> treatment plot was 145% of the realized GPP, which means that already a considerable nitrogen limitation existed. But for the ambient CO<sub>2</sub> treatment plot the potential GPP was with 160% of the actual GPP even higher (see Figure 15). However, after the true start of the CO<sub>2</sub>-treatment things turned around. For this period (1998-2008) the potential GPP for the ambient CO<sub>2</sub> treatment was ‘only’ 155% of the realized GPP anymore, but for the elevated CO<sub>2</sub> treatment this value had increased to 163%, with a maximum of 197% in the year 2007 (see Figure 16). A potential stimulation of photosynthetic carbon fixation by an increase in the atmospheric CO<sub>2</sub> content is obviously severely hampered by a lack of nitrogen in the forest ecosystem. Possibly, this effect is less severe in reality since the enhanced root growth in the elevated CO<sub>2</sub> treatment plots might be a mechanism of the trees to improve their nitrogen uptake from the soil.



**Figure 16 Potential GPP (without nitrogen limitation) per realized GPP for the ambient and elevated CO<sub>2</sub> treatment simulations from 1988, the year after planting, to 2008.**

After comparing these simulated productivity indicators for the two treatments, we can compare simulated net primary production with measurements (see Figure 17). Measurement

data were available from Norby et al. (2008b). The NPP determined at the Oak Ridge FACE experiment is approximately 22 percent higher for the elevated CO<sub>2</sub> treatment during the first five years of the experiment (1998-2002). This relative stimulation of the net primary productivity by the atmospheric CO<sub>2</sub> enrichment however decreases to an average stimulation of roughly 13 percent for the second five years (2003-2007). Also, absolute values show a strong decreasing trend for both treatments beginning in the fifth year of the treatment. I won't discuss these results here in big detail, since this topic has already been addressed in several papers or presentations by the scientists at the Oak Ridge FACE experiment and my task was not the collection of data for the NPP but the computer-simulation of the experiment. Only in short, as a likely reason for the decline in productivity a possible increasing nitrogen limitation at the site is discussed (Norby and Iversen, 2006).



**Figure 17 Simulated and measured net primary production (NPP) for ambient and elevated CO<sub>2</sub> treatment plots at the Oak Ridge FACA site for the years 1997-2006.**

As already discussed earlier, the simulated elevated CO<sub>2</sub> treatment plot has only a slightly higher NPP than the ambient CO<sub>2</sub> plot. This difference shows an increasing tendency, though. For the first five years of the treatment the average difference is less than 2 percent. During the next five years the relative difference increases and is 6 percent on average. The simulated NPP shows much less variation among the years. The trend of decreasing NPP in later years seen at the FACE site is also not clearly visible in the model results. Simulated NPP is considerably lower than what was measured at the site. Only during the last three years

differences between predictions and observations get considerably lower and in 2006 and 2007 observations lie slightly below simulations. Reasons can be manifold and range from possible different model performance during changing climatic situations in different years (e.g. dry vs. wet years) over the problem of fixed allocation and C/N ratios and missing consideration of extreme events like late frost or snow or wind damage to uncertainties in long term changes of plant nitrogen uptake, storage and availability over the forest development cycle. Further analysis, however, would go too far now and shall be done in a next study.

#### **4.1.2 Soil carbon**

Interpretation of simulated soil carbon stocks has to consider the shortcomings in land-use history representation (see chapter 3.2.3). Absolute numbers have to be taken with caution – actually a soil carbon content of 7.4 kg C m<sup>-2</sup> was determined for the early 1990s (van Miegroet et al., 1994) – but trends are worth being interpreted. Soil carbon stocks show a steady decline during the first twenty years after planting (Figure 18) what is also commonly observed in nature after a disturbance like a clearcut with subsequent planting. This trend might or might not have occurred if grassland had been simulated for several decades before the forest establishment.

The reason for the soil carbon decline after clearcut/planting intervention is an altered light and water regime of the forest floor that enhances the degradation of soil organic material. The net carbon loss from the soil usually stops after a couple of years and soil carbon stocks start to increase again. With the simulations until 2008 we might have reached the turning point of the soil carbon development, since the decline was less intense during the last few simulation years and from 2007 to 2008 the soil carbon stock for the elevated CO<sub>2</sub> treatment plot increases for the first time. Overall, its decline followed a shallower curve since planting than the soil carbon decline of the ambient CO<sub>2</sub> treatment plot. Probably, this mainly is a combined effect of different C/N ratios and allocation patterns for the two treatments. Further influencing aspects can be different light and water regimes. The higher C/N ratio especially of the elevated CO<sub>2</sub> leaf litter implies its lower degradability by soil microorganisms. This leads to a higher accumulation of less degradable dead plant material in the soil. Besides, relatively more carbon of the total carbon available is allocated to fine roots. Fine root C/N does not change with the treatment, but with a fine root turnover of 1 year more carbon gets added to the soil organic matter pool every year since relatively less carbon is allocated to the long lived plant compartments.



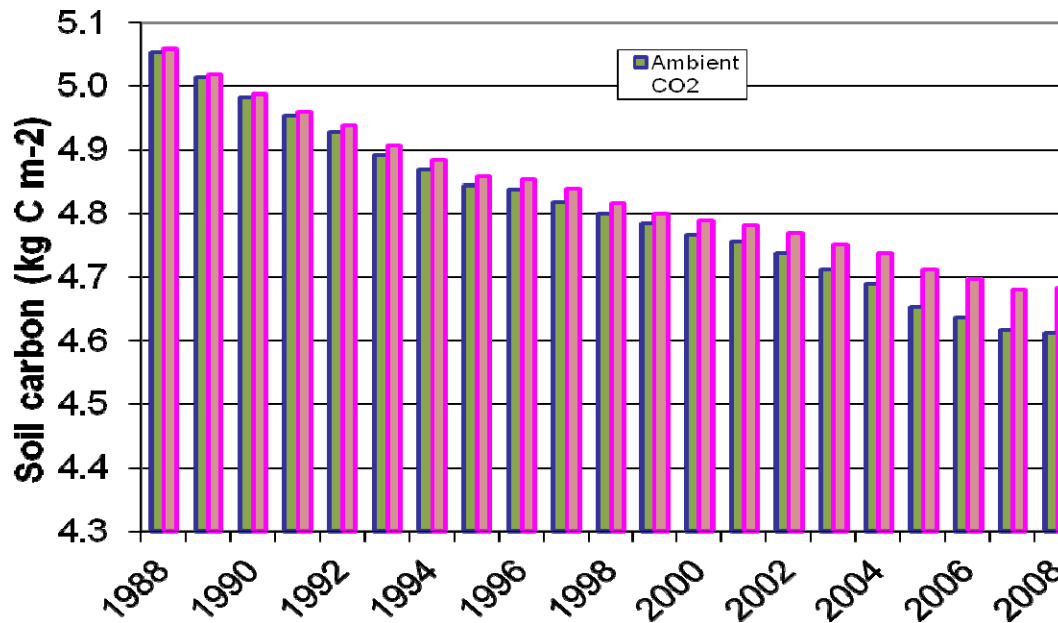


Figure 18 Total soil carbon of the simulated ambient and elevated CO<sub>2</sub> plots, values for December, 31<sup>st</sup>.

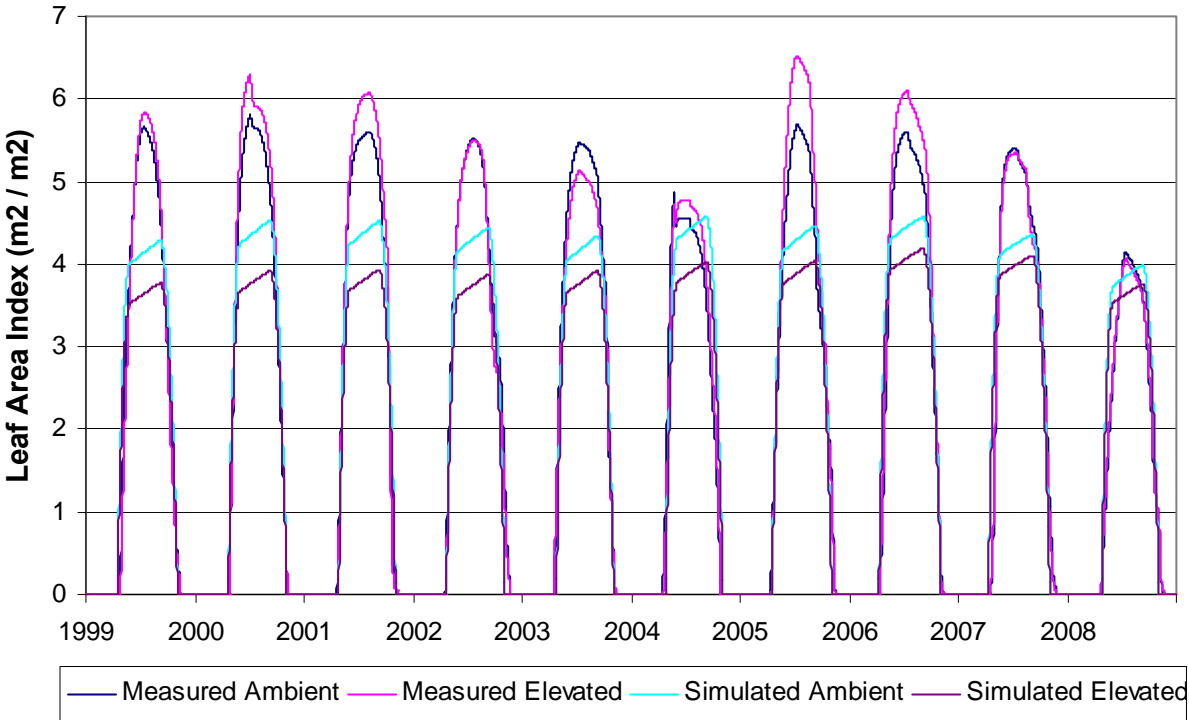
## 4.2 Water budget

The water cycle in the forest ecosystem cannot be treated independently from other cycles. The most relevant compartments where these interactions happen in the model are the canopy and the soil. Since water input, except for those cases where the forest has access to groundwater, happens through the atmosphere a discussion of water budget related study results may begin with the canopy water interactions. Our first look therefore goes to the canopy structure, i.e. the leaf area index LAI.

It depends on the leaf area how much precipitation water is intercepted and how much goes directly into the soil to replenish the soil water pool from which the plants can draw their water. The leaf area primarily depends on the amount of carbon that got allocated into the canopy and the morphological patterns of sun and shade leaves and their relative abundance. Sun leaves e.g. have a lower specific leaf area than shade leaves, in other words the leaf area of sun leaves per amount of leaf carbon is lower. Simulated LAI-curves for each day of the growing season for the ambient and the elevated CO<sub>2</sub> treatment plots are shown in Figure 19. Measured LAI-curves for both treatments for the whole running time of the experiment were available for comparison (Norby et al., 2008b). They are plotted in the same diagram. Measured LAI primarily lies between 5 and 6, but also values up to a 6.5 and down to almost 4 are possible. Model output LAI mostly is considerably lower, most of the time by even more than one unit. Differences between ambient and elevated CO<sub>2</sub> treatment plots are apparent for measurements as well as for simulations, with the higher differences for the later – but with the opposite order! In the field in 6 out of 10 years the elevated CO<sub>2</sub> treatments

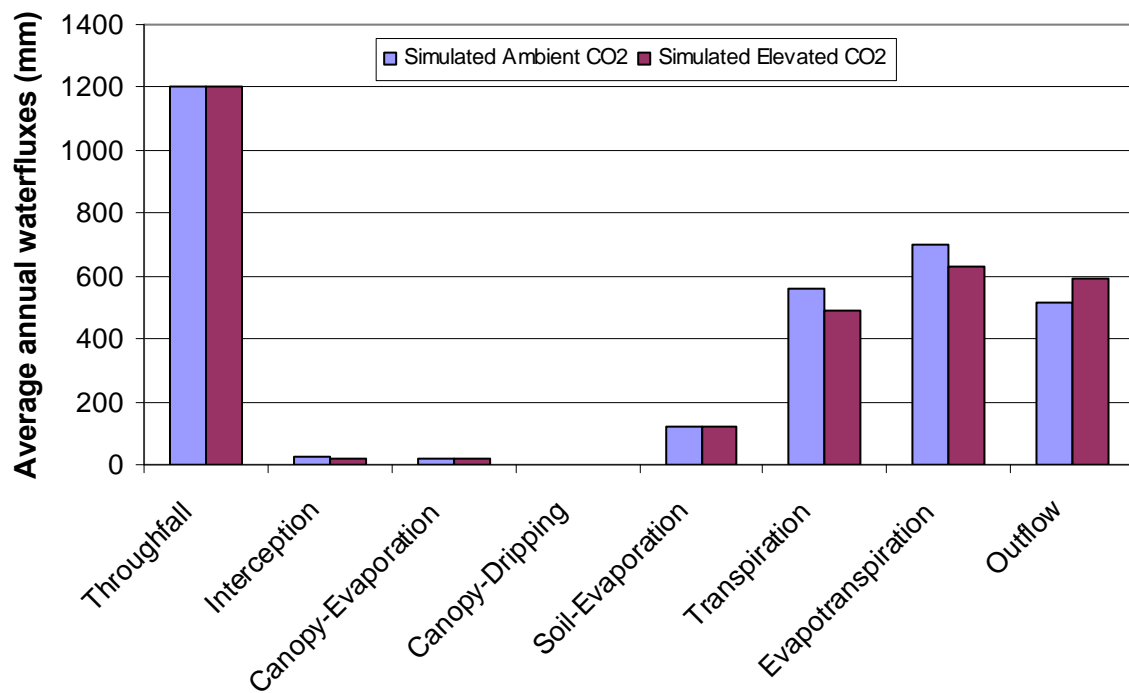
shows a higher LAI than the control plots. Variations between the treatments and among the years are generally high. On the other hand, modeled LAI hardly varies among the years. Only in 2008, when also observed LAI was very low, modeled LAI has similarly low values. As one explanation, why measured LAI in contrast to predicted LAI shows significant differences in peak values among the years, some observed extreme weather events can serve. For example, in May 2004 a storm hit the Oak Ridge FACE site a caused a 10 percent loss of the foliage. LAI increased slightly again after this event, but the peak value stayed below a LAI of five. Only in the year of a severe drought the LAI was even lower.

The most striking difference between simulations and observations is that predicted LAI for the elevated CO<sub>2</sub> treatment is always lower than the ambient CO<sub>2</sub> plot. This can be interpreted as a result of the highly different allocation ratio fine root carbon to leaf carbon for ambient and elevated CO<sub>2</sub> plots, with relatively much more carbon being allocated into roots for the elevated CO<sub>2</sub> plot. This would not per se lead to a lower LAI for this plot, but obviously the primary production is not high enough to compensate for this lower relative carbon allocation into the leaves. A likely reason for a low primary production was already discussed in the previous paragraph. We need to discuss now, what effect the in the model maybe not yet accurately enough represented LAI has on the water budget.



**Figure 19 Simulated and measured leaf area index (LAI) curves for ambient and elevated CO<sub>2</sub> treatment plots at the Oak Ridge FACA site for the years 1999-2008.**

Beginning with precipitation, water entering the ecosystem first gets into contact with the canopy and mainly with the leaf surfaces. A small part of the precipitation gets intercepted by the leaves (see Figure 20) (interception by twigs or the stem is not considered in the model), the rest goes through the canopy to the ground without considerable time lag. Since interception is not a big part of the whole water cycle absolute errors caused by some deficiencies in the LAI calculation are small. From Figure 20 the fate of the intercepted water gets obvious. Through the process of evaporation all this canopy water is directly brought back to the atmosphere. Canopy water dripping would take place if during the day the radiative force was not strong enough to volatilize all the water until the evening. Only water still on the leaves in the evening would then get accounted to the soil water pool. The other and much more important way how the canopy and the water are related is through transpiration. In order to have water available for transpiration we need to close the water cycle in the forest ecosystem first.



**Figure 20 Average water budget for the years 1998 – 2008 simulated with the Biome-BGC model for the ambient and the elevated CO<sub>2</sub> treatment plots at the Oak Ridge FACE site.**

Water not intercepted is also called throughfall. This water enters the soil water pool and a part may be lost immediately, if soil water saturation has already been reached. A slower outflow is simulated when the soil water potential lies above the field capacity. Evaporation is another way by which soil water content gets reduced. Here the canopy structure plays

already a role again, since the LAI determines the amount of radiation energy reaching the ground and acting as a driving force for evaporation. Since light is exponentially attenuated by the canopy according to the Beer-Lambert Law the difference in short wave solar radiation reaching the ground between a LAI of 4 and a LAI of 6 is less than 10% of the above canopy radiation. Therefore, soil evaporation from the elevated CO<sub>2</sub> plot with the smaller LAI won't differ much from soil evaporation from the ambient CO<sub>2</sub> plot. This assumption is confirmed by looking at the soil-evaporation output (see Figure 20).

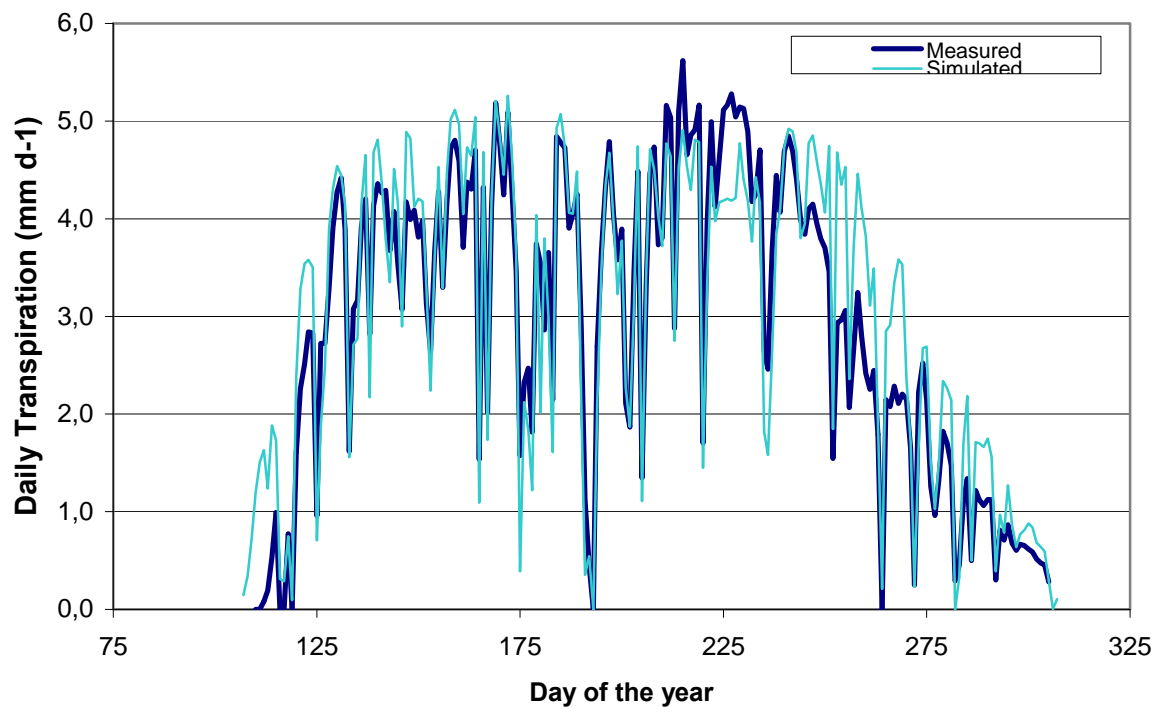
Transpiration is now the last but, in order similar to outflow, also the second main process that draws from the soil water pool. Transpiration is also the only part of the water budget for which data from the FACE site are available. More, the analysis and comparison of observed and predicted transpiration was the main focus of this study. Three years of measured transpiration data were used in the original study, but due to so far missing publication of the later two years only data for 1999 can be presented in this report. A paper presenting and discussing simulation and observation data for the years 2004 and 2008 is in preparation (Wullschleger, Warren, Pötzelsberger, Thornton and Norby, in prep.).

At the Oak Ridge FACE site transpiration was derived from sap flow measurements at a range of different trees per plot (for more details see chapter 3.1.2 and especially Wullschleger and Norby, 2001 and Wullschleger, Warren, Pötzelsberger, Thornton and Norby, in prep.). These data were cleaned and aggregated to get one representative daily transpiration curve over the whole growing season per treatment.

The model directly gives daily transpiration values as an output. Transpiration depends on the temperature, incident solar radiation, atmospheric pressure, vapor pressure deficit, soil water potential, daily minimum temperature (influencing stomatal conductance) the canopy conductance and the time available for transpiration. The canopy conductance is calculated from the boundary layer conductance, total stomatal conductance for sun and shade leaves multiplied with the one-sided LAI of sun and shade leaves and the cuticular conductance. Transpiration does not occur as long as interception water remains in the canopy and time available for transpiration gets reduced.

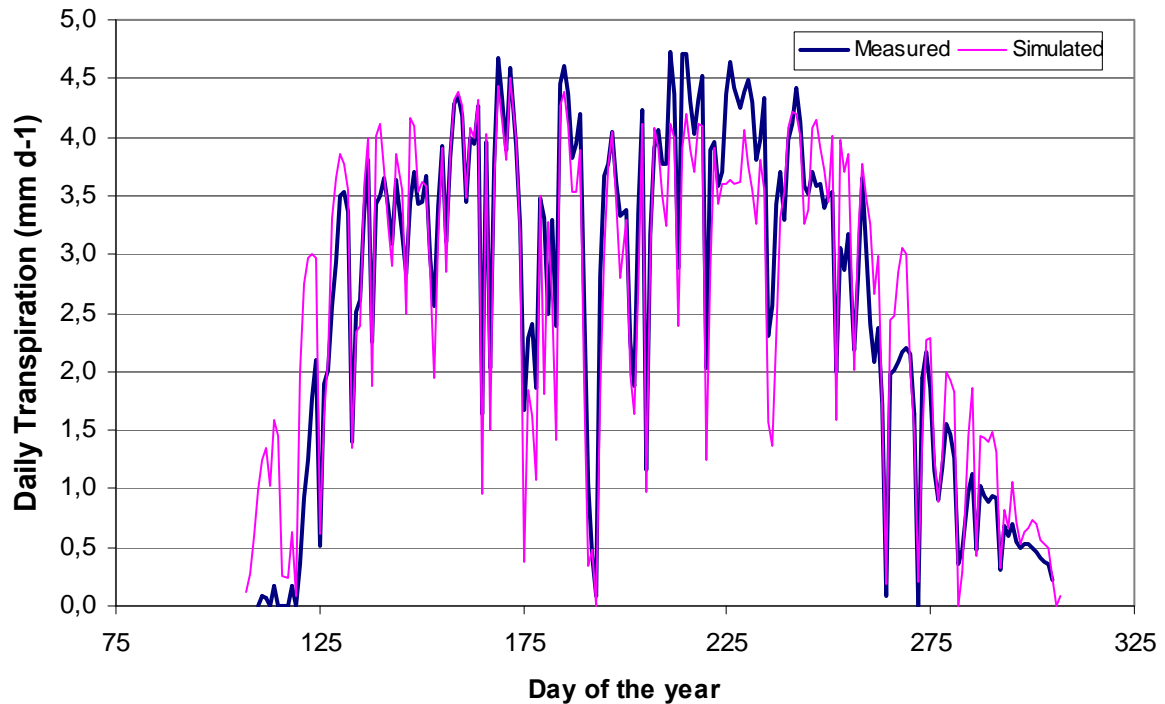
Observed and predicted daily transpiration data can be easily compared per treatment (see Figure 21 and Figure 22). The overall fit of the simulated data to the measured data is good. For 1999 total annual transpiration observed for the ambient CO<sub>2</sub> treatment was 575 mm whereas predictions summed up to 604 mm per year. For the elevated CO<sub>2</sub> treatment observed annual transpiration was 514 mm and predicted annual transpiration was 518 mm. Both, observation and predictions show significantly lower annual transpiration for the elevated

CO<sub>2</sub> treatment. This effect has already extensively been discussed in the literature. Higher CO<sub>2</sub> content of the atmosphere causes a tendency towards higher stomata closure in all kinds of plant leaves. Maximum daily transpiration is also lower for the elevated CO<sub>2</sub> treatment in the observations as well as in the predictions. Day to day variability doesn't seem to be effected, though.



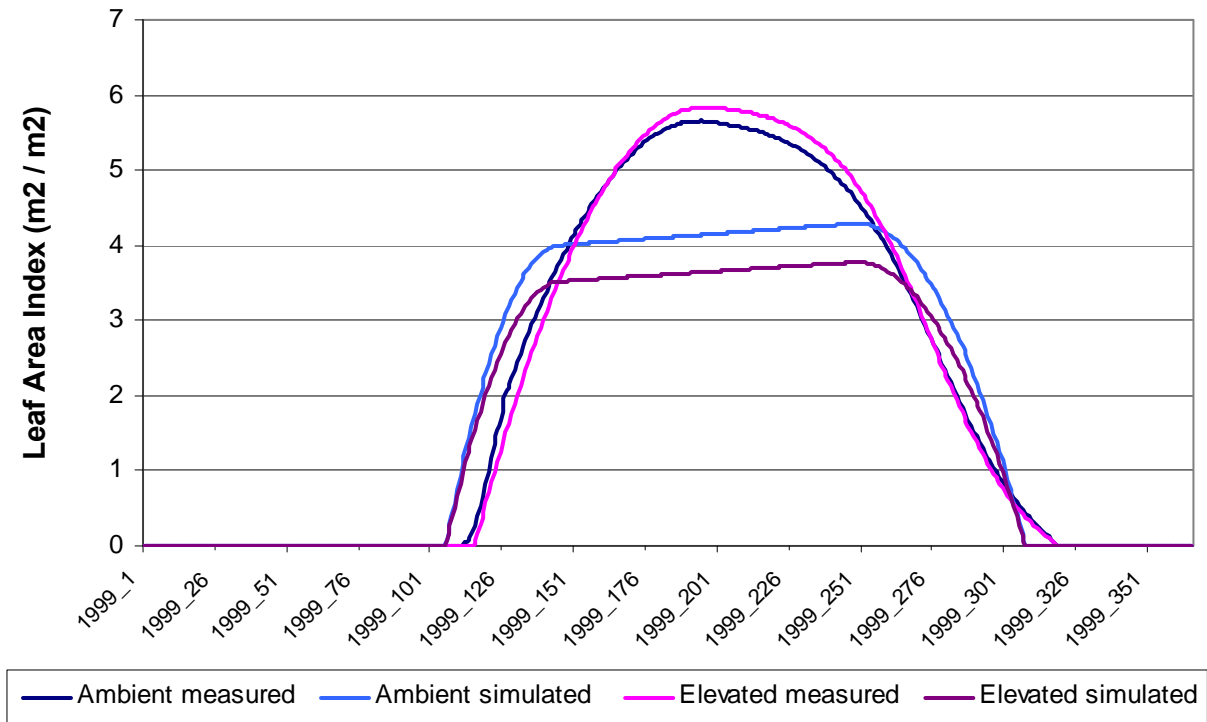
**Figure 21** Daily transpiration measured at American Sweetgum trees (aggregated data shown here) under ambient CO<sub>2</sub> treatment at the Oak Ridge FACE site and Biome-BGC simulations of daily transpiration for the same treatment for the year 1999.

During some periods the peaks differ more between observations and predictions, but in general, the observed day to day variations with the smaller and larger ups and downs are well represented in the model. One of the biggest differences between predictions and observations is apparent right at the beginning of the growing season. For this year the beginning of leaf flushing obviously was set too early (see Figure 23) with the consequence that simulated transpiration has already picked up when in the forest the leaves only start to grow. For the elevated CO<sub>2</sub> treatment this effect is even more pronounced for the year 1999. However, as was already shown in Figure 14, there is year to year change in the order of leaf flushing for the two treatments. The same figure makes it also clear that a simulated too early flushing is not always the case and therefore too high early spring transpiration is not a general result. What is more a general model characteristic is too high transpiration during the litterfall period.



**Figure 22** Daily transpiration measured at American Sweetgum trees (aggregated data shown here) under elevated CO<sub>2</sub> treatment at the Oak Ridge FACE site and Biome-BGC simulations of daily transpiration for the same treatment for the year 1999.

Approximately at yearday 250 a systematic overestimation of daily transpiration sets in. Two things probably cause this trend. On the one hand, the process of litterfall is not represented in sufficient detail in the model. The shape of the observed and predicted LAI-curves differs – which means that obviously not the optimal litterfall-function is implemented in the model – and the underestimation of LAI earlier in the season turns into an overestimation. One could argue that the underestimation of LAI in mid season should actually cause an underestimation of transpiration. In fact, at a relatively high LAI this LAI difference does not have a very high impact on simulated daily transpiration since smaller LAI primarily means less shade leaves which only have a low stomatal conductivity due to stomata closure caused by low irradiation. However, in autumn when the LAI is already relatively small a similar LAI difference (but in this case with a different order!) can have a higher impact on the accuracy of simulated transpiration, since less stomata closure induced due to less shading by the fewer other leaves.



**Figure 23 Leaf area index observed and simulated for ambient and elevated CO<sub>2</sub> treatment at the Oak Ridge FACE site for 1999.**

The other aspect that might add to overestimation of transpiration in autumn is that it is assumed that leaves are fully functional till they get abscised. This does not represent reality, though, for leaves start to shut down their metabolism earlier (otherwise it would not be possible that the litter C/N ratio is about double of the leaf C/N ratio) and they mostly are wilted or have necroses on at least parts of the leaf surface before they fall. This aspect is not considered in the model and is very likely to play a key role in the overestimation of late season transpiration. In Figure 24 leaves from an elevated CO<sub>2</sub> treatment plot at the Oak Ridge FACE site can be seen. They were harvest beginning of September for a test of temperature stress on their photosynthetic activity. The coloration and spots of necrosis are not a result from this experiment, but had begun to develop already several days before as the normal sign of approaching end of the growing season.

For a more extensive and detailed discussion on the water budget at the Oak Ridge FACE site and especially on daily transpiration measurements and simulations for different years I want to refer to here to Wullschleger, Warren, Pötzelberger, Thornton and Norby, in prep..





**Figure 24** *Liquidambar styraciflua* leaves showing coloration and spots of necrosis from an elevated CO<sub>2</sub> treatment plot at the Oak Ridge Face site harvested on September 4<sup>th</sup>, 2009.

## 5 Summary and Conclusions

Some of the most pressing questions in ecology and in the light of the climate change debate also of today's society are the fate of the carbon in our ecosystems and especially in our forests since they hold the highest carbon stocks of all terrestrial ecosystems. Accordingly, the investigation and prediction of the performance of forests under changing environmental conditions is a crucial field of science that more and more people pay attention to. In the study of the possible effects of rising atmospheric CO<sub>2</sub> content and changing climate both, manipulative ecosystem experiments (with e.g. controlled atmospheric CO<sub>2</sub> content, temperature and/or precipitation) and process based model simulations are essential tools that ideally go hand in hand.

Similar to the issues just mentioned, the topic of my PhD-thesis will be the possible effect of rising atmospheric CO<sub>2</sub> and climate change on European Beech forests in the West Pannonian Basin in the boarder region of Austria and Hungary. The question is, how a raising CO<sub>2</sub> content and higher temperatures and summer droughts that are likely to increase in intensity and frequency will effect the productivity of these Beech forests that have already strongly



suffered under low precipitation during the growing season in some regions of the project area in recent years. The mechanistic ecosystem model Biome-BGC will be applied to analyze the possible effects on the carbon and water fluxes in these forest ecosystems. Unfortunately, no data are currently available from manipulative forest ecosystem studies in that region, which could be used to test the model performance under altered CO<sub>2</sub> and climate conditions. Since a general model test is indispensable it was a great opportunity for me to go to the USA, where some different ‘free air CO<sub>2</sub> enrichment’ (FACE) experiments are conducted. There, I got access to data from the Oak Ridge FACE experiment and could scrutinize the Biome-BGC model and simulation results under the supervision of Peter Thornton, one of the main Biome-BGC model developers.

A study was conducted together with scientists from the Oak Ridge National Laboratory, where data on the carbon, nitrogen and water budget of an American Sweetgum, (*Liquidambar styraciflua*) plantation grown under approximately 550 ppm atmospheric CO<sub>2</sub> content for the last 12 years were compiled, analyzed and used for model parameterization and testing.

First of all, two ecophysiological parameterizations for *Liquidambar styraciflua* needed to be done, i.e. for the elevated CO<sub>2</sub> treatment and the reference plot, the ambient CO<sub>2</sub> treatment. Data on NPP and carbon and nitrogen content of the different plant compartments were used to determine the carbon allocation ratios and the C/N ratios, respectively. Leaf and canopy anatomy and physiology information also served the model parameterization. Additional ecophysiological parameters were taken from the literature or personally assessed. Site constants information could be taken from publications and daily weather and atmospheric CO<sub>2</sub> content data were available from the online FACE data management system.

Some other difficulties existed for the simulation of the historic landuse, since with the current model version a switch from forest to grassland and again back to forest was not possible. A good representation of the landuse history is important to account for changes in the carbon and nitrogen stocks in the soil. This problem could not be totally solved so far, however for this study where the focus actually lied on the water budget, the effect on the most interesting output variables was low. For future studies with focus on the carbon cycle this problem, which is rather a computer technical one, needs to be tackled, though.

Early simulations made it obvious that adaptations of the phenology and the soil water potential calculation were necessary. Without corrected parameters in the soil water routine the soil water potential dropped too quickly in times of limited rainfall and accordingly

drought stress occurred too early. This induced stomatal closure with negative effects on the water and carbon fluxes.

After the necessary model amendments detailed analysis of model results and their comparison with measurements were possible, especially for the NPP, LAI and most importantly for this study, the daily transpiration. Overall, simulated NPP and LAI were rather underestimated, especially for the elevated CO<sub>2</sub> treatment, what can have something to do with a nitrogen limitation even stronger in the model than allegedly observed at the site. This might have been caused by an insufficiency in the simulation of the nitrogen deposition, or, for the elevated CO<sub>2</sub> treatment, by the missing advantage of increased fineroot growth for the plant that had been observed at the site and consequently had to be incorporated into the ecophysiological parameterization. This didn't have a strong impact on the simulation of the water budget, though. The LAI was still high enough to play its characteristic role in the cycling of water through the ecosystem realistically. Simulated daily transpiration overall fitted well to daily transpiration values derived from sap flow measurements at the site. The strong day to day variations in transpiration were captured very well by the model and the generally lower transpiration of the elevated CO<sub>2</sub> could also be shown with the model. A detailed discussion of more transpiration observations and predictions not presented in this report is in preparation (Wullschleger, Warren, Pötzelsberger, Thornton and Norby, in prep.). This study gave very important insight into the model capacity to simulate forest ecosystem response to elevated atmospheric CO<sub>2</sub> and climate change. The theory and knowledge gained from this modeling study using data from American Sweetgum FACE experiment can be applied also to other deciduous broadleaved forests, like European Beech forests in the West Pannonian Basin, an area likely to be severely hit by negative impacts of climate change, especially summer drought. Since the atmospheric CO<sub>2</sub> content has a significant impact on transpiration through stomatal opening the analysis of results from the FACE experiment will be very helpful for simulations planned for my PhD-thesis, as will be the various more model-experimental results and the many theoretical discussions with people from the Numerical Terradynamic Simulation Group from the University of Missoula, Montana, with scientists from the Oak Ridge National Laboratory working on the Oak Ridge FACE experiment and especially with Peter Thornton, the extremely skilled, but also very generous and supportive key-developer of the Biome-BGC model.

Therefore, I want to express as a final remark my deepest gratitude to the Austrian Marshall-Plan Foundation that enabled this so interesting and fruitful stay in the USA to me!

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