Project No. 037005

CECILIA

Central and Eastern Europe Climate Change Impact and Vulnerability Assessment

Specific targeted research project

1.1.6.3.I.3.2: Climate change impacts in central-eastern Europe

D 6.7: Integrated assessment of climate change and air pollution impacts on C-cycle in agriculture and on forest ecosystems

Due date of deliverable: 31st Dec, 2009

Actual submission date: 31st Dec, 2009

Start date of project: 1st June 2006 Duration: 43 months

Lead contractor for this deliverable: Department of Meteorology, Eötvös Loránd University (ELU)

Revison [FINAL]

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Contents

CARBON

1. Introduction

Earth's climate is closely coupled with the greenhouse gas content of its atmosphere (Jansen et al., 2007). At present the most important anthropogenic greenhouse gas is carbon dioxide (CO_2), which is also used by plants to build their own body via photosynthesis. Through photosynthesis carbon is taken up from the atmosphere in the form of CO_2 thus decreasing the amount of the atmospheric CO_2 concentration. Plants also respire CO_2 to produce energy for their life processes. Soil and litter also respire, since the organic carbon that is stored in these pools is continuously decomposed by microbes. There is a fine balance in most of the terrestrial ecosystems between carbon uptake and carbon release that can be altered by climate change, air pollution and human intervention (Friedlingstein et al., 2006).

Currently terrestrial biosphere mitigates climate change since part of the anthropogenically released CO_2 is sequestered in terrestrial ecosystems (0.9±0.6 GtC/year net uptake of the 7.2±0.3 GtC/year fossil CO_2 emission; Denman et al., 2007). As the carbon sequestration capacity of ecosystems depend on a series of environmental factors, it is challenging to predict the future carbon balance of the biosphere. Air pollution and climate change will act parallel as main drivers of ecosystem productivity. State-of-the-art biogeochemical models, capable to describe present day carbon budget with good accuracy, are needed to simulate future carbon cycle in different ecosystems.

Central-Eastern Europe is located in a vulnerable zone where the strength of climate change might be amplified by a factor of ~1.2-1.5 as compared to the global average (Christensen, 2005; Bartholy et al., 2007). According to recent findings storm tracks may shift northward in the future which might trigger droughts and heat spells in Central Europe (Schär et al., 2004; Giorgi and Coppola, 2007). Severe droughts can be associated with carbon loss in ecosystems (Ciais et al., 2005; Haszpra et al., 2005; Vetter et al., 2007), which acts as a positive feedback to climate change. Because of the strong coupling between the biogeochemical cycle of carbon in the soil-plant system and the climate, the understanding of the global carbon cycle, including its interactions and feedbacks is a prerequisite to any reliable climate prediction (Cox et al., 2000; Friedlingstein et al., 2006; Denman et al., 2007). The prediction about the fate of the global carbon cycle is essential to provide information to policy makers about the steps required to mitigate climate change and its socio-economic effects.

Prior to the application of biogeochemical models to simulate future carbon cycle on continental or global scale, it is essential to test the models at plot level, for different plant functional types. The aim of the present study is to calibrate the BIOME-BGC model at plot level for typical forest and agricultural ecosystems in Poland, Slovakia and Hungary, and to use the model with the climate change scenario data provided by other workpackages of the CECILIA project.

Besides meteorological data air pollution is also taken into account in the model in the form of predicted elevated atmospheric CO_2 concentration and increased nitrogen deposition due to human activities. This integrated assessment is used to separate the effect of meteorological drivers and other environmental factors in the changing carbon cycle of unmanaged forests and managed agricultural regions. In our approach the ambient CO_2 concentration is prescribed (SRES data; Nakicenovic et al., 2000). Since the calculations are performed at plot level, there is no joint relation between the changing carbon balance and the atmospheric CO_2 concentration.

2. Modelling approach

2.1 The BIOME-BGC model

BIOME-BGC is a process based mechanistic biogeochemical model that can be used to simulate carbon, nitrogen and water fluxes of different terrestrial ecosystems (deciduous and evergreen forests, grasslands, shrubs; Running and Coughlan, 1988; Running and Gower, 1991; Running and Hunt, 1993; White et al., 2000; Churkina et al., 2003; Hidy et al., 2007). Recently some researchers started to evaluate the model's applicability for croplands (Wang et al., 2005; Vetter et al., 2007; Barcza et al, 2009). BIOME-BGC is well documented, and most importantly the parameterisation of the model is documented in details (Thornton, 2000; White et al., 2000).

BIOME-BGC requires three groups of information: (1) daily meteorological data; (2) geomorphologic and soil characteristics, and environmental data; (3) biome specific ecophysiological parameters.

The minimum meteorological data requirement to use BIOME-BGC is daily maximum and minimum temperature, and daily sum of precipitation. All other meteorological data can be calculated with additional software. BIOME-BGC is generally used together with the MT-CLIM model so as to keep the required meteorological input data minimal. MT-CLIM estimates mean daytime vapor pressure deficit, mean daytime global radiation and mean daytime temperature from daily minimum/maximum temperature and precipitation data (Kimball et al., 1997; Thornton and Running, 1999; Tatarinov and Cienciala, 2006). In the present study we only used daily minimum/maximum temperature and daily precipitation sum data from the high resolution climate scenario dataset in order to provide consistent dataset.

The required geomorphological and soil parameters include physical soil properties (sand/silt/clay content of the soil), effective soil depth, shortwave albedo, site elevation and latitude. Environmental data includes atmospheric nitrogen deposition, biological nitrogen fixation and ambient CO_2 concentration. Ambient CO_2 concentration is related to air pollution since CO_2 can also be considered as pollutant in the sense that it causes undesirable changes in the environment. Nitrogen containing reactive atmospheric compounds are originating mainly from human activities and they have a strong interaction with the terrestrial biosphere (Dentner et al., 2006). BIOME-BGC is one of the few models that handle nitrogen cycle thus the effect of air pollution can be scrutinized directly through the nitrogen cycle of the ecosystem.

The ecophysiological parameters of the model include information about carbon and nitrogen allocation in the different plant pools, quality of litter, plant mortality, root turnover, stomatal conductance, water interception, etc. For a full description of the ecophysiological parameters we refer to Thornton (2000) and White et al. (2000). BIOME-BGC is published with a default parameterzation for each plant functional types, which provides a robust estimate of the biological carbon fluxes globally (White et al., 2000). At plot level the performance of the model can be dramatically improved if the parameters are adjusted to reflect local conditions, i.e. the model is calibrated (Hidy et al., 2007). This is generally carried out using measurement data, which can be biomass related information from forest inventories or eddy covariance data e.g. from the worldwide FLUXNET network (Baldocchi et al., 2001). It is important to keep in mind that the calibration of a complex, non-linear, multiparameter model such as BIOME-BGC is challenging task and cannot always be used successfully due to equifinality in the parameter sets (Hollinger and Richardson, 2005).

In order to use BIOME-BGC, the initial carbon and nitrogen pools of a given ecosystem have to be estimated. As the direct measurement of these pools is difficult and labour intensive, BIOME-BGC model users generally utilize the spin-up option of the model to estimate the initial values of the state variables (Thornton, 2000; Churkina et al., 2003). During spin-up a several hundred years long period is simulated to achieve the equilibrium with the present climate using a long-term meteorological data record. The spin-up simulation creates an endpoint file for the initialization of the normal simulation. The endpoint file contains information about the equilibrium carbon and nitrogen pools of the ecosystem. BIOME-BGC users generally apply preindustrial CO_2 concentration and nitrogen deposition data for the spin-up phase (Churkina et al., 2003). In the normal simulation phase actual CO_2 concentration and nitrogen deposition data are used.

2.2 Modelling approach with BIOME-BGC

We use BIOME-BGC v4.1.1. to simulate the present and future carbon cycle of unmanaged forests in Poland and Slovakia, managed grassland and agricultural land in Hungary. Site specific measurement dataset is used in all cases for the calibration of the model.

Forest carbon cycle is simulated for unmanaged forests in Poland and Slovakia. For the simulation of unmanaged forests no modification in the model logic is needed. The only modification applied is the simulation of clearcut following the method of Thornton et al. (2002) and Tatarinov and Cienciala (2006). This includes modification of the endpoint file in order to rearrange carbon pools and represent removal of aboveground biomass from the site.

At the grassland site the grass is mowed twice a year (Barcza et al., 2003). As management is not included in BIOME-BGC we made modification in the model logic in order to simulate the harvest. At the time of mowing a fraction of the aboveground biomass is taken away from the site and is excluded from further calculations. According to the experiences the modified model performs better after the incorporation of management. For the future carbon cycle business-as-usual management is assumed, which means two mowings in every year.

In case of mixed agricultural croplands we use the "supergrass" approach (Vetter et al. 2007, Barcza et al. 2009). As the measured net ecosystem CO_2 exchange (NEE) is balanced in time at the agricultural site (see Haszpra et al., 2005), the carbon cycle of the croplands is estimated based on the model's grassland parameterization. As harvest (i.e. horizontal carbon transport) is not included in this model version, the assumption causes overestimation of respiration (Barcza et al., 2009). This overestimation causes problems but as the main goal is to estimate the direction and magnitude of the *change* in the carbon cycle due to air pollution and climate change, this kind of simplification is acceptable in the present context. We need further research in order to provide better estimates for managed agricultural carbon cycle.

In the followings we introduce the datasets that we used for the calibration and simulations. Site-specific datasets and the results of the calibration will be presented in separate sections together with the presentation of site-specific simulations and impact analysis.

<u>Meteorological data</u>

For the spin-up phase of the simulation long-term historical meteorology data are needed. For that purpose we use CRU TS 1.2 data (10 minute resolution gridded dataset, monthly mean temperature, daily temperature range, precipitation; New et al., 2002). We used the C2W weather generator to create daily data based on the monthly means (Bürger, 1997). The MT-CLIM model (see Section 2.1) was used for the estimation of the missing meteorological variables (mean daytime vapour pressure deficit, mean daytime global radiation and mean daytime temperature).

For the present day simulation we used the interpolated daily meteorological fields from the ENSEMBLES FP6 project (Haylock et al., 2008[1]). This gridded dataset contains daily maximum/minimum temperature and daily precipitation amount data at 0.25 degree resolution, for the period of 1950-2006. We also used the MT-CLIM here for the estimation of the other parameters.

Climate scenario data was produced by WP2 of the CECILIA project for the time slices of 2021-2050 and 2071-2100 using the A1B SRES scenario (Nakicenovic et al., 2000). We used output of regional climate model simulations performed by the Eötvös Loránd University (Hungarian RegCM-beta; referred to as RegCM HU), the Hungarian Meteorological Service (Aladin-Climate; referred to as Aladin HU), the Czech Hydrometeorological Institute (Aladin-Climate/CZ; referred to as Aladin CHMI), and the Charles University of Prague (referred to as RegCM CUNI). Global climate

[1] see also http://eca.knmi.nl/download/ensembles/download.php

models ARPEGE-Climat (Meteo-France) and ECHAM5 provided the driving data of the regional models.

As there might be a systematic over- or underestimation in the precipitation scenarios we used the CRU TS 1.2 data and the simulation data from the reference period (1961-90) to estimate bias. The calculated bias was used to correct the future precipitation scenario data.

The missing intervals (2008-2020, 2051-2070) were filled following the method of Morales et al. (2007). As the Morales et al. (2007) method creates monthly estimates for the transient periods, the C2W daily weather generator was also used here to create daily dataset.

Air pollution data I: CO_2

Historical CO_2 mixing ratio data was estimated based on the Law Dome ice core measurements (Etheridge et al., 1998) and the Mauna Loa observations (Keeling and Whorf, 2004). The two datasets were combined to provide one continuous estimate. For the estimation of the future CO_2 concentration the SRES data were used (Nakicenovic et al., 2000). As the SRES data were available for decades, spline interpolation was used to create annual dataset. The final continuous dataset is consistent with the historical data.

Air pollution data II: atmospheric nitrogen deposition

As a consequence of air pollution the atmospheric deposition of reactive nitrogen compounds has increased (Churkina et al., 2003; Dentener et al., 2006). The measurement of total nitrogen deposition is difficult and such data is not available for our target regions. Thus we used model output for the reconstruction of the past nitrogen deposition. We used the annual data published by Dentener et al. (2006) from 1860-2000. This dataset contains annual nitrogen deposition in 1° by 1° global resolution. In order to estimate the future evolution of nitrogen deposition we used the dataset provided by Dentener (2006). This latter dataset has a resolution of 5° by 3.5° and provides nitrogen deposition data at three dates: 1860, 1993 and 2050. In the present work nitrogen deposition is linearly interpolated between 2000 and 2050 (values available as predicted by data from Dentener et al., (2006) and Dentener (2006), respectively), then the same rate is prolonged until 2100. In an alternative scenario the 2000 nitrogen deposition is held constant until 2100. In this manner the effect of nitrogen deposition can be recognized in the changes.

Model calibration

For the calibration of the BIOME-BGC model for forest ecosystems we used the approach of Cienciala and Tatarinov (2006). Their approach is based on the sensitivity analysis presented by Tatarinov and Cienciala (2006). As the ecophysiological parameters are available from the literature, Cienciala and Tatarinov (2006) proposed that model calibration should involve only two site parameters: biological (symbiotic and asymbiotic) nitrogen fixation and effective soil depth. Both parameters are difficult to measure, thus it is reasonable to perform model calibration in order to find the most appropriate values of these two important parameters. Effective soil depth in BIOME-BGC is not directly related to the real soil depth but rather it is the depth of the bucket used for the soil moisture calculations, while in the same time it equals the rooting depth (G. Churkina, personal communication). Thus the calibrated soil depth might strongly deviate from the measured one.

For the estimation of the effective soil depth and the biological nitrogen fixation we used the Monte Carlo Maximum Likelihood (MCML) method. The MCML algorithm uses the Monte Carlo method to generate random values in a given *a priori* interval. The model is run with the random parameters and the model output is compared with the measurements. A merit function is constructed from the measurement data and model output and the final aim is to find the maximum likelihood (minimal error) parameter set. The two parameters that provide the maximum likelihood are used in the present day and scenario simulations.

For agriculture related simulations literature based model parameters are not available, thus the above procedure cannot be performed. Instead, we use a Bayesian approach to calibrate the model for the managed grassland, and Monte Carlo Maximum Likelihood method to do the same for the mixed agricultural land (Hidy et al., 2007; Barcza et al., 2009). In the Bayesian and MCML approaches the sensitive ecophysiological parameters are varied simultaneously while the geomorphological and soil parameters are held constant. The statistical analysis is performed based on the measured eddy covariance dataset that provide direct information about the carbon exchange of the managed grassland and the mixed agricultural region (Barcza et al., 2003; Haszpra et al., 2005). The calibrated parameter sets are derived from the results of the Monte Carlo analysis for both cases.

3. Kampinos forest - Poland

3.1 Site description

Kampinos National Park (in Polish: Kampinoski Park Narodowy) situated in east-central Poland, is the second largest out of 23 National Parks in Poland (after Biebrza National Park). Due to the diversity of natural environment, the area of the Park constitutes one of the most crucial refuges of the Polish lowland fauna. It is included in the UNESCO-MaB Biosphere Reserve Programme as well as into the NATURA 2000 network. Moreover, the Park was recognised as a refuge for birds on a European scale by the European Parliament.

The Park is located in Masovian Voivodeship, on the north-west outskirts of Warsaw, at the biggest river junction in Poland. Here valleys of Vistula, Bug, Narew, Wkra and Bzura meet together. There are no lakes, the biggest river of the Park is the Łasica, a tributary to the Bzura, which acts as a water canal. Kampinos belongs to the Mazowsze-Podlasie natural-forest region. The current Park area equals 38 544 ha, 12% of which is under strict protection. The protective zone around the Park covers 37 756 ha.

The climate of the Kampinos park is influenced by continental and oceanic climate. The average yearly temperature equals to 7.8 °C, while yearly precipitation amounts to 530 mm. Frequent windless periods are a characteristic feature of the Kampinos forest weather. Due to the sandy soil and low annual precipitation the forest ecosystem is vulnerable to drought and fire (the Park is categorized in 1st level of fire risk in Polish forest fire risk scale). Consequently, the ongoing climate change might severely affect its carbon cycle and productivity.

The Kampinos area is characterized by a great diversity of plants. It comprises about 1370 vascular plant species, including 74 species under strict protection, as well as 100 moss species and 150 lichen species. Forests account for over 70% of Park area with pine being the most common tree species. The dunes are overgrown by pine forests with a mixture of deciduous trees, mainly oaks.

As the dominant tree species is Scots pine, this study focuses on the assessment of climate change and air pollution impact on the carbon cycle of pine forest located in the Kampinos National Park. Since measurement data used for model calibration were available from diverse sources, it was not possible to define a single target plot for the study. We conducted simulation for a virtual forest plot inside the Kampinos park (52°20'31'' N, 20°38'47'' E). As the soil type and climate are similar for the entire Park, the present results can be interpreted as representative for the whole park.

3.2 Data and methods

Calibration of the BIOME-BGC evergreen needleleaf forest (ENF) submodel for Kampinos was performed using the approach proposed by Cienciala and Tatarinov (2006). As model parameterization regarding the ecophysiological variables is available from the literature for Scots pine (*Pinus sylvestris* L.), we made no attempt to refine the ecophysiological parameters. The modeling approach was to use three available parameterizations in order to estimate the uncertainty in the carbon cycle related scenarios resulting from parameter uncertainty. The three parameterizations for pine were taken from Churkina et al. (2003) (in the following referred to as Churkina parameterization), Pietsch et al. (2005) (referred to as Pietsch parameterization) and Cienciala and Tatarinov (2006) (referred to as Cienciala parameterization). The main differences between the parameterizations can be seen in Table 3.2.1.

As it was pointed out by Cienciala and Tatarinov (2006) during the spin-up phase of the simulations the steady-state carbon pools should be in accordance with those estimates available from the literature. If some of the equilibrium pools (e.g. soil or litter carbon pool) are over/underestimated, it may cause bias in the simulations for the present and especially for the future. To address this issue we made modifications in the ecophysiological parameters during the spin-up phase according to

Tatarinov and Cienciala (2006). The modifications were made in the 'annual whole-plant mortality fraction' and 'annual fire mortality fraction' parameters. The resulting equilibrium carbon pools are comparable with Adams (1997). At the end of the spin-up phase a clearcut is simulated (the pine forest was planted around 1935). The simulation of clearcut was performed following the method published by Thornton et al. (2002) and Tatarinov and Cienciala (2006). Tree plantation is simulated with a minimum set of initial foliage and stem carbon pools (Cienciala and Tatarinov, 2006).

PARAMETER	UNIT	PARAMETER VALUE		
		Cienciala	Pietsch	Churkina
(ALLOCATION) new fine root C : new leaf C	(ratio)	1	0.523	1.4
(ALLOCATION) new croot C : new stem C	(ratio)	0.44	0.29	0.29
C:N of dead wood	(kgC/kgN)	730	1400	730
canopy water interception coefficient	(1/LAI/d)	0.051	0.051	0.00025
maximum stomatal conductance (projected area basis)	(m/s)	0.0025	0.001	0.006
cuticular conductance (projected area basis)	(m/s)	0.00006	0.00001	0.00006
vapor pressure deficit: start of conductance reduction	(Pa)	600	50	610

Table 3.2.1. Main differences between the three parameterizations.

Model calibration involved two site parameters: biological (symbiotic and asymbiotic) nitrogen fixation and effective soil depth. Monte Carlo Maximum Likelihood method was used in the calibration of the two parameters. In order to check the goodness of the model simulations we made a literature search overview regarding the Kampinos forest (Table 3.2.2). Data from Józefaciukowa (1975) were used for the calibration. Data from the forest monitoring program nearby Kampinos were also used in the work. These data were taken from Permanent Observation Plot II level (Wawrzoniak et al., 2000; pine stem increment data, Table 3.2.2.).

The calibration results show that effective soil depth is rather small – it varies between 0.12 m and 0.37 m. Note that these values are lower than the 'rule-of-thumb' estimates due to the inaccurate soil water submodel of BIOME-BGC. The results suggest that in sandy soils water stress can only be simulated with low effective soil depth.

Biological nitrogen fixation is estimated to be low: according to the calibration results it is around 1.4×10^{-5} and 4.2×10^{-5} kgN/m^2/year depending on the parameterization used.

CARBON POOL/ CARBON POOL INCREMENT	MEASURED	MODELLED Pietsch param.	MODELLED Cienciala param.	MODELLED Churkina param.
leaf C 1975 (kgC/m^2)	0.19	0.374	0.189	0.273
stem C 1975 (kgC/m^2)	13.03	10.89	10.858	9.274
root C 1975 (kgC/m^2)	3.71	3.35	4.959	3.068
coarse root C 1975 (kgC/m^2)	2.08	3.158	4.777	2.689
root increment 1968-1972 (kgC/m^2/year)	0.047	0.04	0.058	0.029
stem increment 1990-1994 (kgC/m^2/year)	0.095	0.067	0.088	0.063
stem increment 1985-1994 (kgC/m^2/year)	0.092	0.08	0.098	0.056
stem increment 1995-1999 (kgC/m^2/year)	0.128	0.138	0.162	0.109
stem increment 1990-1999 (kgC/m^2/year)	0.118	0.103	0.125	0.086

Table 3.2.2. Measured and modeled carbon pools and rate of changes in some carbon pools for Kampinos forest. Measurement data were compiled from Józefaciukowa (1975) and Wawrzoniak et al. (2000). The modelled data are based on the different parameterizations of the calibrated BIOME-BGC evergreen needleleaf forest (ENF) submodel (see text for the citations). Note that in BIOME-BGC stem represents total aboveground woody biomass (including stem and branches).

The simulations were performed with the same air pollution data but with different parameterization and one regional climate model output data (RegCM CUNI). Fig. 3.2.1. shows the atmospheric CO_2 concentration according to the A1B scenario (Nakicenovic et al., 2000), the estimated nitrogen deposition data (Dentener, 2006), the mean annual temperature and annual precipitation sum based on the regional climate model data for Kampinos. All simulations were performed for the time period of 1935-2100. In order to estimate the effect of air pollution on the carbon cycle model simulations were performed with nitrogen deposition and CO_2 concentration held at the year 2000 level.

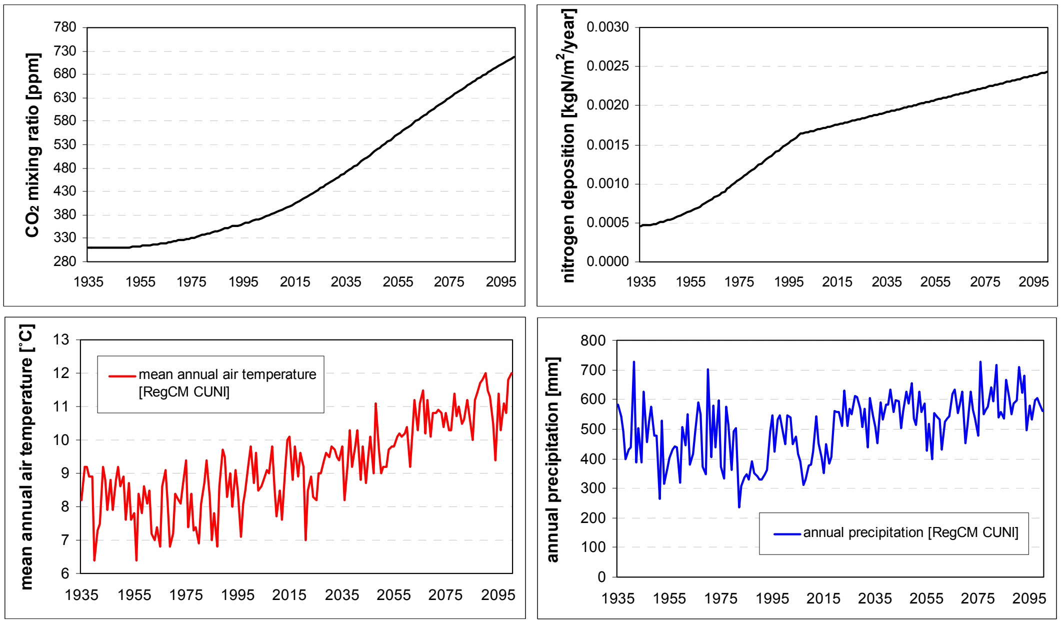

Fig. 3.2.1. Upper left: evolution of the atmospheric CO_2 mixing ratio (1935-2100, A1B scenario). Upper right: evolution of the atmospheric nitrogen deposition (1935-2100). Lower left: mean annual temperature at Kampinos based on the regional climate model RegCM CUNI used in the present analysis (1935-2100). Lower right: annual precipitation sum at Kampinos based on RegCM CUNI model (1935-2100).

3.3 Integrated assessment of climate change and air pollution impacts on C-cycle in Kampinos forest

Forests take up CO_2 from the atmosphere to build their own woody biomass and foliage, and they sequester carbon for long time periods. This sequestration is mainly attributed to biomass increment, though forest soils can also store significant amount of carbon for many years. As a consequence, reforestation and afforestation are believed to mitigate climate change as forests can take up CO_2 from the atmosphere released by anthropogenic emission.

Measurement evidence showed that the carbon sequestration potential of forests can be reduced due to extreme weather conditions (Ciais et al., 2005). Model results suggest that forests for larger regions can eventually release carbon in specific environmental conditions instead of taking up carbon on annual basis (Barcza et al., 2009). If regional climate change will increase the number of extreme weather situations causing carbon release events, the carbon sequestration capability of forests can decrease which may act as a positive feedback to warming.

We have performed evergreen needleleaf forest specific simulations with the BIOME-BGC model utilizing the methodology described in detail in Section 2.2. Air pollution impact was taken into account through the CO_2 fertilization effect caused by the increasing atmospheric CO_2 concentration and the increasing nitrogen deposition arising from industrial and agricultural activities. Climate change impact is taken into account with the application of high resolution regional climate model simulation results performed by WP2 of the CECILIA project.

Changes in carbon content of IPCC pools, increments and carbon fluxes with climate change and increasing air pollution

First, we analysed the evolution of the carbon content of forest carbon pools according to IPCC (2003). The evolution of these pools (Fig. 3.3.1.) shows that carbon content is increasing continuously in all pools during the simulated period (1935-2100). This means that Kampinos forest will likely be able to sequester CO_2 in the future.

It is difficult to estimate the exact amount of carbon stored in different pools because the value of certain input parameters can be measured with difficulty. It depends on many factors, e.g. on geographical location, site conditions, and sampling methodology. Reviews point out that there can be either a magnitude of difference between the results of carbon pool calculation methods (for biomass, see e.g. Zianis et al., 2005).

Belowground biomass and soil carbon pool show the biggest variability among the simulations. The huge difference in carbon content of belowground biomass is probably caused by the differences in the allocation parameter “new coarse root C : new stem C” (Table 3.2.1.). Since BIOME-BGC is a highly nonlinear model, we can hardly explain the other differences simply with the different ecophysiological parameters. Further analyses and measurements are required to constrain the model for the given site conditions.

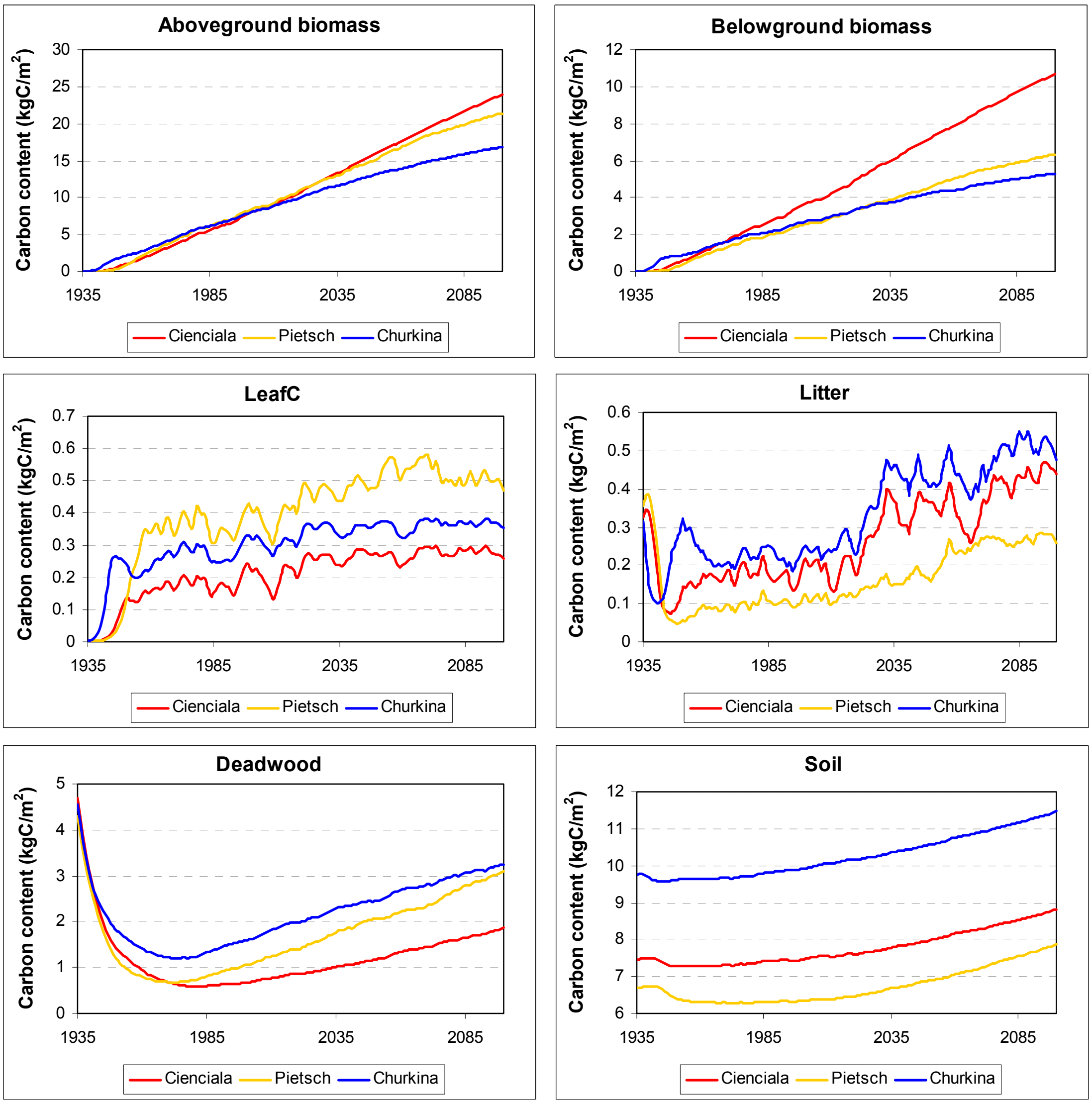

Figure 3.3.1. Simulated evolution of the carbon content of IPCC pools for the Kampinos forest from 1935 to 2100 using different parameterizations.

We analysed the impact of environmental change on increments (i.e. the difference in carbon content of stem and root pools between the consecutive years). Fig. 3.3.2. shows the evolution of root and stem increments. Though mean annual temperature, atmospheric CO_2 concentration and N deposition show an increasing tendency and annual precipitation shows relatively large variability (Fig. 3.2.1.), we didn't observe any significant tendencies in increments in the examined period (1935-2100).

We performed a boxcar averaging (running mean) analysis to learn more about the simulated tendencies (Fig. 3.3.3.). In case of root increment no tendency can be seen. Stem increment shows a decreasing tendency after 2050 according to all parameterizations. (Churkina parameterization shows this decreasing tendency from 1975. In contrast, there is an increasing period from 2000 to 2050 according to the two other parameterizations.)

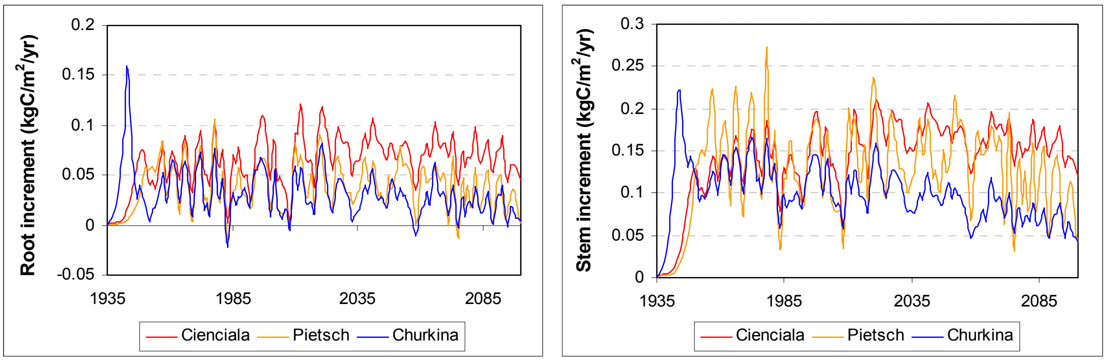

Figure 3.3.2. Simulated evolution of root and stem increment for the Kampinos forest from 1935 to 2100 using different parameterizations.

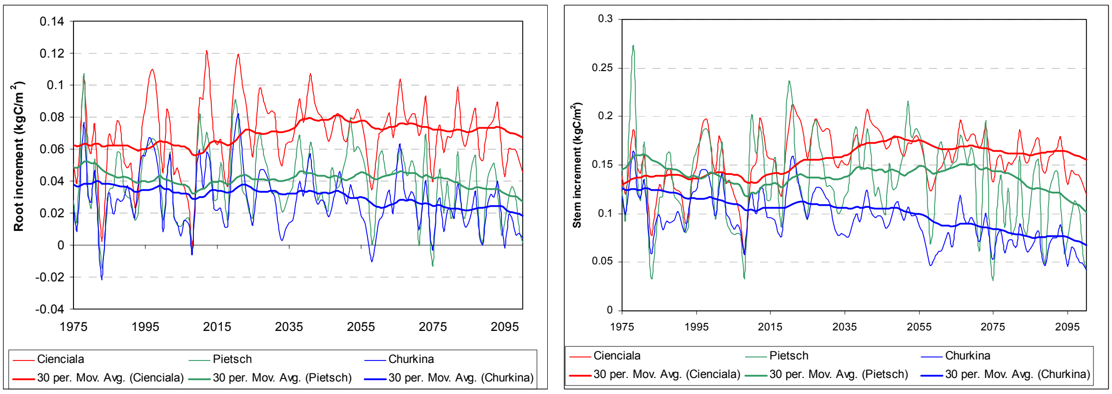

Figure 3.3.3. Annual and 30-years moving averages of root and stem increments for the period of 1975-2100.

Multimodel average increments (calculated as the mean of the three simulations performed with the three different parameterizations) for 1971-2000, 2021-2050 and 2071-2100 periods do not show either any clear tendency. Average root increments for these periods are 0.047, 0.051 and 0.038 $kgC/m^2/yr$, while average stem increments are 0.13, 0.14, 0.11 $kgC/m^2/yr$, respectively.

Root increment turned into negative a couple of times during the simulation period. This means that in these years the amount of carbon stored in roots is smaller than in the previous year. Stem carbon doesn't show this phenomenon, it is always positive.

We performed a regression analysis between increments and climate change components (change in mean annual temperature and annual precipitation). The correlation coefficients strongly varied among the parameterizations (Table 3.3.1.). Significant positive correlation was found between increments and annual precipitation in case of Cienciala parameterization. In case of Churkina parameterization, a negative correlation was found between mean annual temperature and increments. In case of Pietsch parameterization, no significant correlation was found between increments and climate change components. The three parameterizations showed completely different results so we cannot formulate a general statement of increments' dependence on the meteorological parameters.

R^2 values	Cienciala	Pietsch	Churkina
precipitation – stem increment	0.404	0.046	0.001
precipitation – root increment	0.280	0.055	0.039
temperature – stem increment	0.025	0.104	*0.410*
temperature – root increment	0.000	0.074	*0.150*

Table 3.3.1. Square of the correlation coefficient (i.e. explained variance) between annual precipitation, mean annual air temperature and carbon pool increments based on the different parameterizations. Italic numbers indicate negative R values.

An ecosystem's carbon balance is generally described with the main carbon fluxes of the ecosystem from the point of view of the atmosphere. Carbon uptake from the atmosphere (in the form of CO_2) via photosynthesis is called gross primary production (GPP). Total ecosystem respiration (Reco, the amount of CO_2 that increases the atmospheric CO_2 content) is the sum of respiration of the plant itself (autotrophic respiration, Ra), and respiration of heterotrophs (heterotrophic respiration, Rh). Net ecosystem exchange (NEE) is the net carbon balance of the ecosystem if there is no horizontal carbon displacement and it is defined as GPP+Reco. In the present study negative values indicate CO_2 (or carbon) removal from the atmosphere, while a positive value marks CO_2 (or carbon) loss from the ecosystem. For example, negative NEE means net carbon uptake by the vegetation. In this sense GPP is always negative, as it describes carbon uptake via photosynthesis, and respiration is always positive.

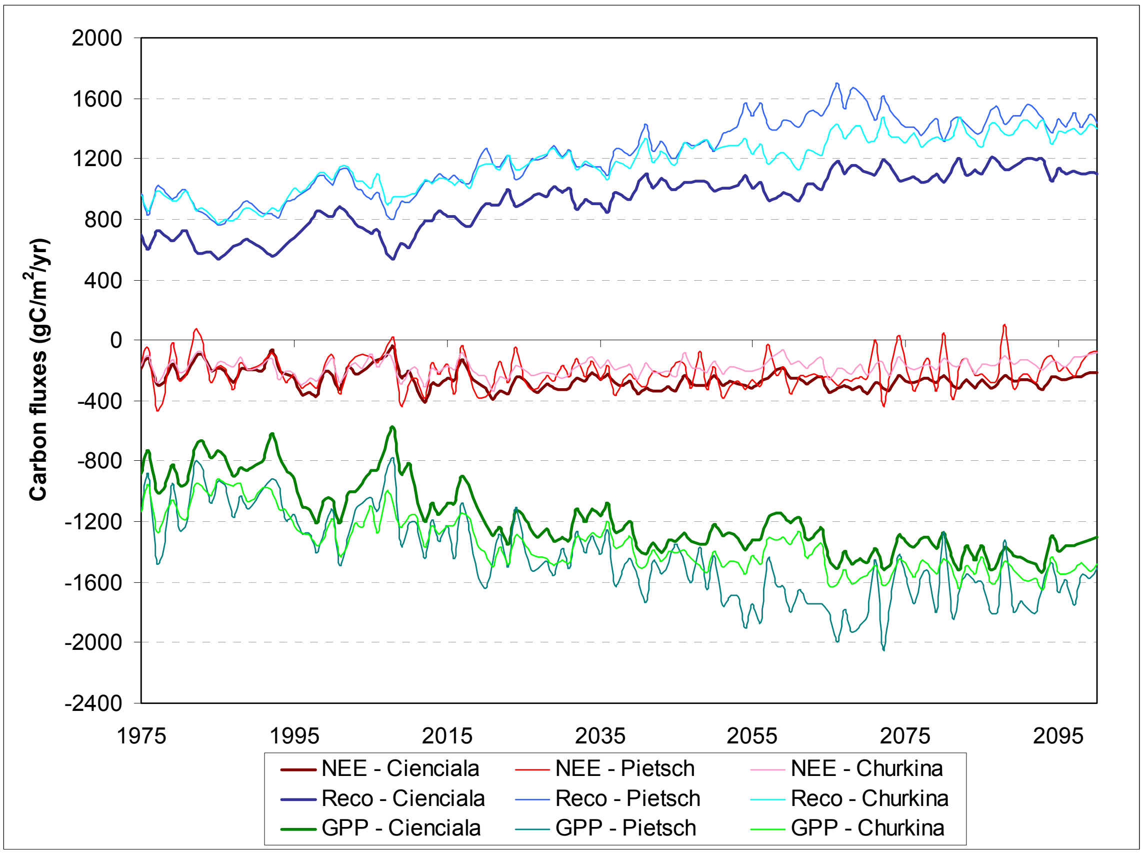

Figure 3.3.4. Changes in Kampinos forest carbon fluxes between 1975 and 2100 using different parameterizations. Negative values indicate biospheric carbon dioxide uptake by the vegetation from the point of view of the atmosphere.

Fig. 3.3.4. shows the biosphere/atmosphere carbon exchange of the unmanaged Kampinos forest. The magnitude of Kampinos's GPP is increasing continuously. We calculated a multimodel average GPP for the reference periods of 1971-2000, 2021-2050 and 2071-2100 to quantify this tendency. Its values are -1039, -1372 and -1519 gC/m^2/yr, respectively.

Reco is the mechanism by which the whole ecosystem emits CO_2 to the atmosphere. According to our model results Reco is also increasing in time. Its multimodel average values for 1971-2000, 2021-2050 and 2071-2100 are 836, 1131 and 1316 gC/m^2/yr, respectively.

NEE is the sum of GPP (carbon uptake) and Reco (carbon release). In our case it does not show a tendency. Its multimodel average values for 1971-2000, 2021-2050 and 2071-2100 are -202, -241 and -203 gC/m^2/yr, respectively. NEE values are negative which means that the whole Kampinos forest ecosystem will remain net carbon sink in the future. Changes in climate and air pollution do not seem to influence the carbon sequestering capacity of this forest. Although – according to our simulations – there are some years in which NEE exceeds zero (i.e. the forest becomes net carbon source). We found positive NEE values after 2000 in 5 times, and only with the Pietsch input parameterization, so the frequency of this phenomenon seems to be very low.

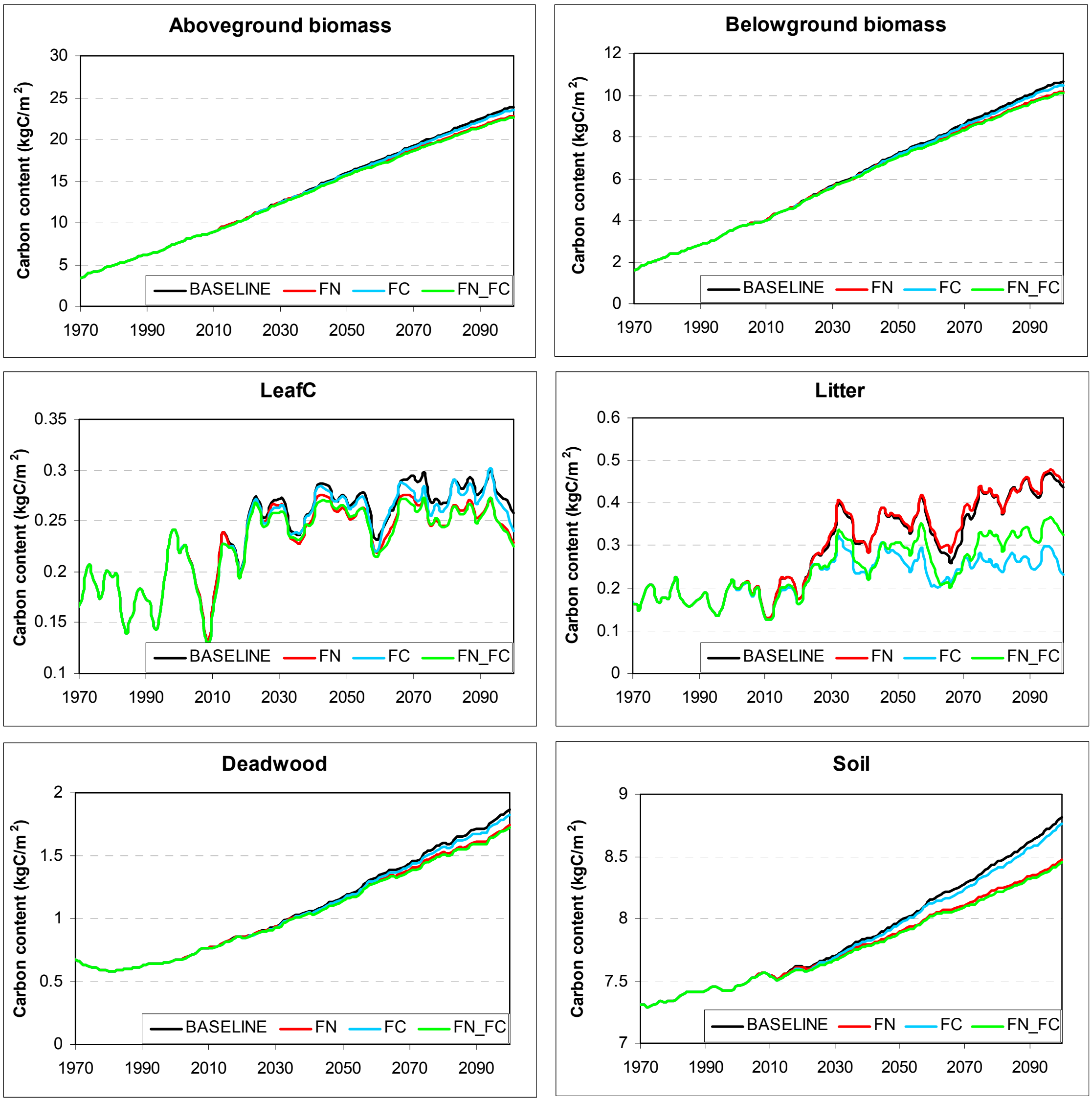

Figure 3.3.5. Changes in carbon content of IPCC pools during 1971-2100 using the parameterization of Cienciala et al. (2006) and different air pollution scenarios (baseline: elevated atmospheric CO_2-concentration and N-deposition; FC: CO_2-concentration fixed at year 2000 level; FN: N-deposition fixed at year 2000 level; FN-FC: CO_2-concentration and N-deposition fixed at year 2000 level).

Impact of air pollution

To analyse the impact of air pollution, we created four different scenarios based on our model simulations: 1) elevated atmospheric CO_2 concentration and N deposition (baseline), 2) CO_2 concentration held at the year 2000 level (FC), 3) N-deposition held at the year 2000 level (FN), 4) CO_2 concentration and N-deposition held at the year 2000 level (FN-FC). For detailed description of air pollution scenarios see Section 2.2.

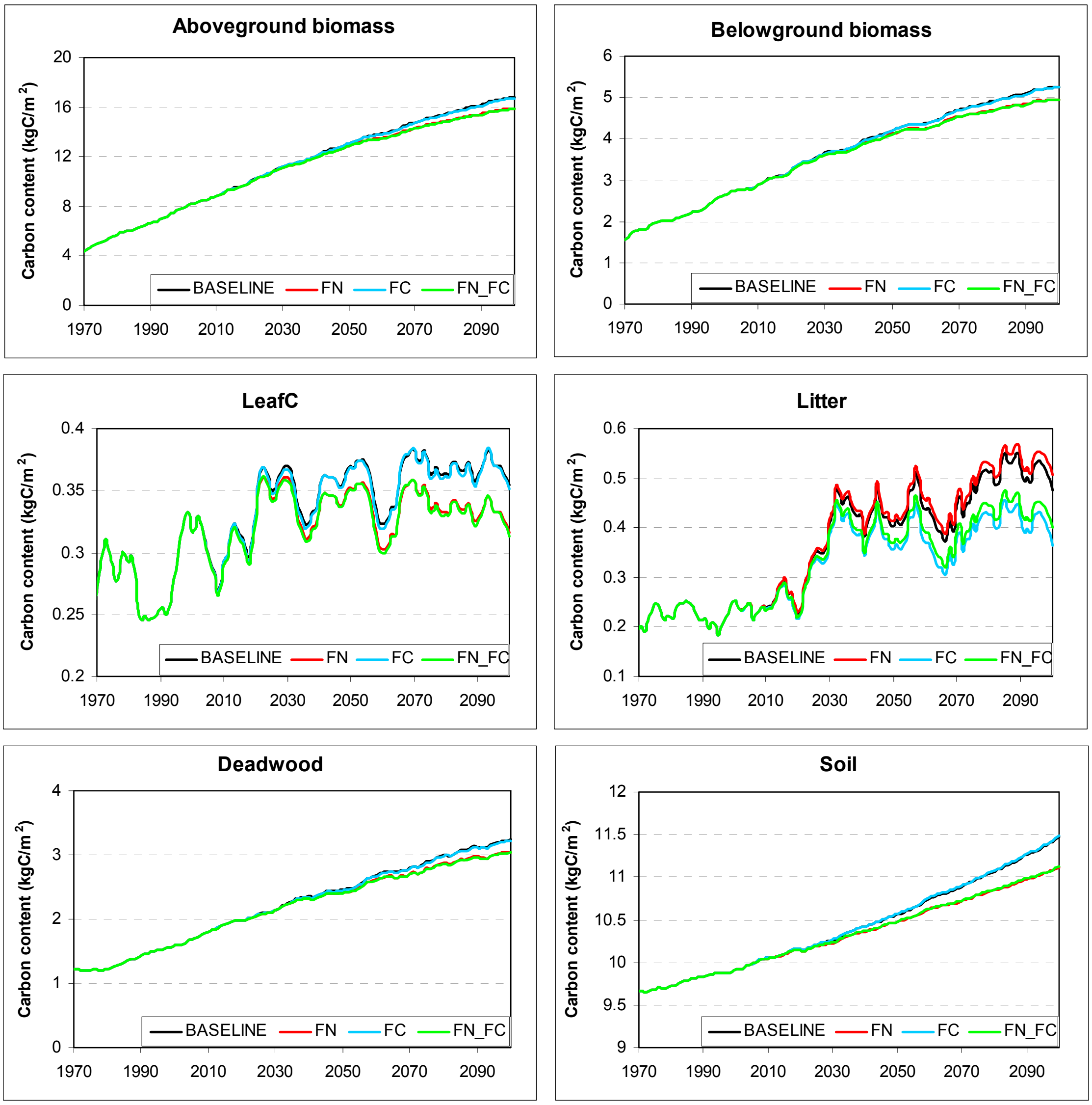

Figure 3.3.6. Changes in carbon content of IPCC pools during 1971-2100 using the parameterization of Churkina et al. (2003) and different air pollution scenarios (baseline: elevated atmospheric CO_2-concentration and N-deposition; FC: CO_2-concentration fixed at year 2000 level; FN: N-deposition fixed at year 2000 level; FN-FC: CO_2-concentration and N-deposition fixed at year 2000 level).

In case of Cienciala (Fig. 3.3.5.) and Churkina (Fig. 3.3.6.) parameterization for almost every IPCC pools, FN scenario showed greater difference than FC relative to baseline. It means that elevated N-fertilization has bigger impact on these pools than elevated atmospheric CO_2-concentration. In case of fixed CO_2-concentration the evolution of IPCC pools is similar to baseline: carbon content of living and dead biomass and soil are also increasing at this rate. In case of litter, elevated CO_2-concentration has bigger impact on this pool.

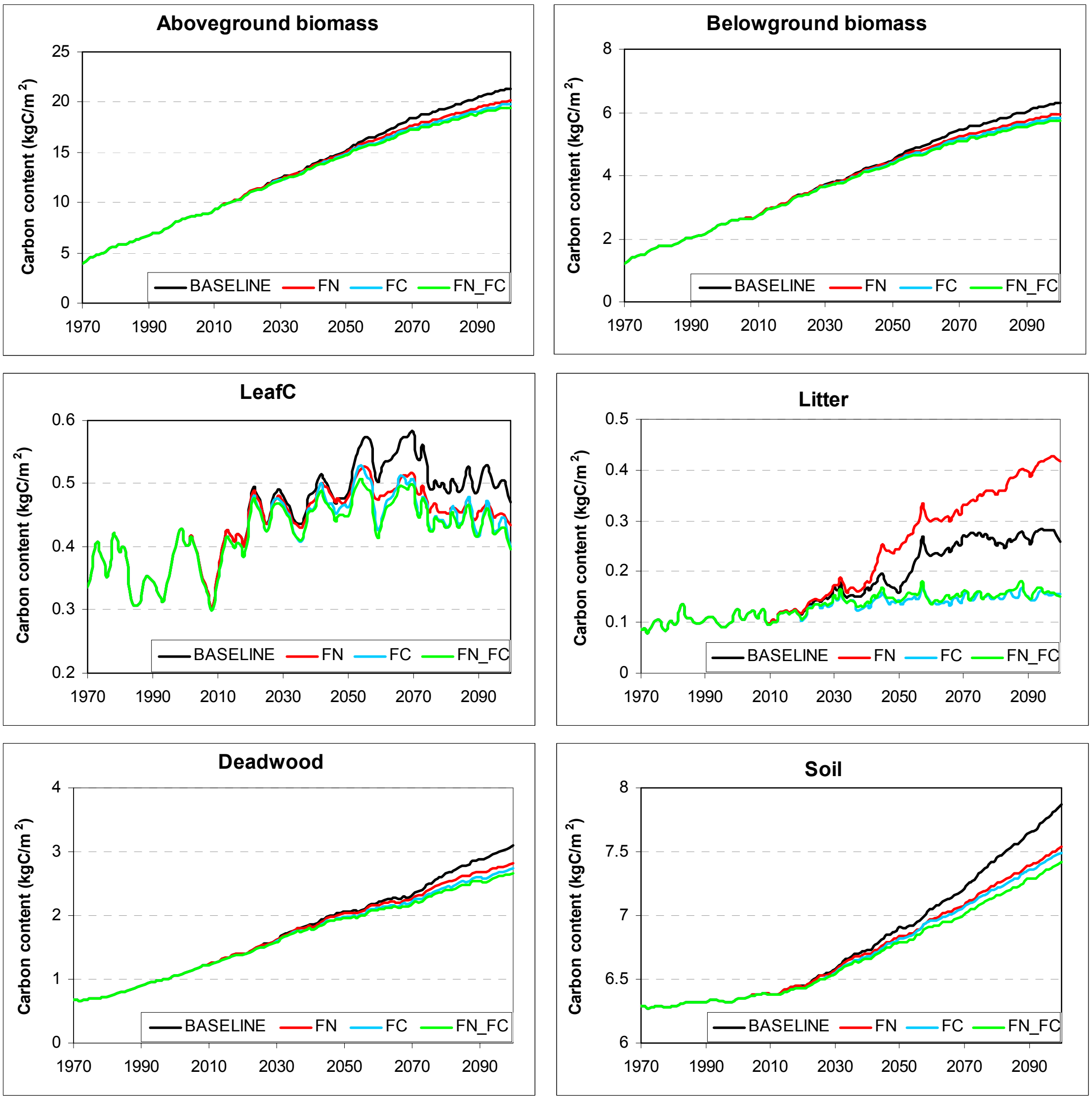

Figure 3.3.7. Changes in carbon content of IPCC pools during 1971-2100 using the parameterization of Pietsch et al. (2005) and different air pollution scenarios (baseline: elevated atmospheric CO_2-concentration and N-deposition; FC: CO_2-concentration fixed at year 2000 level; FN: N-deposition fixed at year 2000 level; FN-FC: CO_2-concentration and N-deposition fixed at year 2000 level).

Different tendencies can be seen in case of Pietsch parameterization (Fig. 3.3.7.). Carbon content of IPCC pools is much bigger in the baseline scenario than in the others. It means that the joint impact of air pollution (elevated atmospheric CO_2-concentration and N-deposition) causes a significantly greater increment in pool size, thus, the carbon sequestration capacity. The three other scenarios show similar results in almost every pool. Litter is an exception, where elevated CO_2-conecntration with fixed N-deposition (FN scenario) causes the biggest pool size.

Root and stem carbon pool increments (Table 3.3.2.) show a similar tendency as the IPCC pools in case of Cienciala and Churkina parameterizations, though the values vary a lot between the different parameterizations (causing 30-50% SD relative to the average). Increments are the biggest in baseline scenario and the smallest in fixed air pollution (FN-FC) scenario. In general, FC values are bigger than FN which means that elevated N-deposition has a bigger impact on increments than CO_2-concentration. The impact of CO_2-concentration can hardly be seen between FN and FN-FC scenarios but it can be observed between baseline and FC scenarios (see Table 3.3.2.) Pietsch parameterization is an exception; here FN values are bigger than FC.

Parameterization	Root increment (kgC/m²/yr)				Stem increment (kgC/m²/yr)			
	BASE	FC	FN	FN-FC	BASE	FC	FN	FN-FC
Cienciala	0.071	0.069	0.066	0.066	0.161	0.158	0.151	0.149
Pietsch	0.038	0.033	0.035	0.033	0.130	0.115	0.119	0.113
Churkina	0.026	0.026	0.023	0.023	0.089	0.088	0.080	0.080
Average	**0.045**	**0.043**	**0.041**	**0.040**	**0.127**	**0.120**	**0.117**	**0.114**
SD	**0.023**	**0.023**	**0.022**	**0.022**	**0.036**	**0.035**	**0.036**	**0.035**

Table 3.3.2. Average carbon pool increments for the 2000-2100 period based on the different air pollution scenarios. BASE: baseline scenario, elevated atmospheric CO_2-concentration and N-deposition; FC: CO_2-concentration fixed at year 2000 level; FN: N-deposition fixed at year 2000 level; FN-FC: CO_2-concentration and N-deposition fixed at year 2000 level. SD: standard deviation.

Parameterization	GPP (gC/m²/yr)				Reco (gC/m²/yr)			
	BASE	FC	FN	FN-FC	BASE	FC	FN	FN-FC
Cienciala	-1257	-1233	-1191	-1179	984	969	939	931
Pietsch	-1522	-1402	-1436	-1380	1305	1214	1239	1197
Churkina	-1413	-1408	-1338	-1333	1236	1233	1179	1176
Average	**-1397**	**-1348**	**-1322**	**-1297**	**1175**	**1139**	**1119**	**1101**
SD	**133.2**	**99.4**	**123.3**	**105.1**	**169.0**	**147.2**	**158.7**	**147.9**

Parameterization	NEE (gC/m²/yr)			
	BASE	FC	FN	FN-FC
Cienciala	-273	-264	-252	-248
Pietsch	-217	-188	-198	-183
Churkina	-177	-175	-159	-157
Average	**-222**	**-209**	**-203**	**-196**
SD	**48.2**	**48.1**	**46.7**	**46.9**

Table 3.3.3. Average carbon fluxes for the period after 2000. BASE: baseline scenario, elevated atmospheric CO_2-concentration and N-deposition, FC: CO_2-concentration fixed at year 2000 level; FN: N-deposition fixed at year 2000 level; FN-FC: CO_2-concentration and N-deposition fixed at year 2000 level. SD: standard deviation.

Scrutinizing biosphere/atmosphere CO_2-exchange, the same tendencies can be seen as for carbon content of IPCC pools and increments (Table 3.3.3.). Overall, the impact of N-deposition is bigger than of CO_2-concentration. Thus, the magnitude of GPP and Reco is bigger in case of FC scenario than in case of FN, except for the Pietsch parameterization where FN values are bigger than FC.

NEE is the signed sum of GPP and Reco. The same tendency can be observed in its values as for GPP and Reco: NEE is the more negative in case of baseline scenario and the less negative in case of FN-FC scenario (more negative NEE means more carbon uptake from the atmosphere). FC values were higher than FN but the Pietsch parameterization is also an exception here.

Average NEE remains negative after 2000. NEE does not exceed zero during the simulation period (after 2000) except in case of Pietsch parameterization. In this case, NEE exceeds zero 5 times in baseline and also FC and FN-FC scenarios and 4 times in FN scenario. This means that vegetation will likely remain net carbon sink in the future. Elevated air pollution modifies plants' growth: plants will have more nutrients (mainly nitrogen) and they can grow faster taking up more CO_2 from the atmosphere. This can reduce the climate change impacts caused by increasing temperature.

4. Čifáre forest - Slovakia

4.1 Site description

Experimental material was gathered at the Čifáre permanent monitoring plot. Plot's size is 50x50m containing 143 Turkey oak (*Quercus cerris* L.) trees in age of 83 years (in 2007). Plot's altitude is 225 m a.s.l., with gentle slope of 15° and south-west exposition. Mean annual air temperature during 1981-2001 was 9.4°C. Mean annual precipitation totals during this period were 544 mm. Soil is relatively heavy clay-loam, loam in the topsoil. Soil medium depth is up to 90 cm. It is rather firm and drying out in the summer period.

The plot represents a model site of oak communities on loess in oak vegetation belt. Shrub layer is well developed, dominated by Blackthorn (*Prunus spinosa* L.), Wild Privet (*Ligustrum vulgare* L.), Hawthorn (Crataegus sp.) and Rose (Rosa sp.). This composition is admixed by European Cornel (*Cornus mas* L.), Common Buckthorn (*Rhamnus cathartica* L.), European White Elm (*Ulmus laevis* Pall.) and Blackberry (*Rubus fruticosus agg.*).

The plot is operated within the frame of European monitoring network (ICP Forests) since 1995. It is well equipped by meteorological, dendrometric and other instruments. Measured parameters and measurement intervals are according to ICP Forest methodology. The main measured parameters are soil conditions and foliage, crown condition and tree damage, atmospheric depositions, litter, soil moisture and trees increment.

4.2 Data and methods

The ecophysiological model parameters for turkey oak (*Quercus cerris* L.) were taken from Pietsch et al. (2005) based on the model parameters published for pedunculate/sessile oak (*Quercus robur/petraea* L.). We modified one allocation related model parameter (ratio of new coarse root C to new stem C) in order to improve the match between the measured and modeled data (see Table 4.2.1. for measurement data). We made no further attempt to refine the ecophysiological parameterization due to the lack of information related to turkey oak.

For the spin-up phase of the simulation we used the methodology described in section 3.2. The resulting equilibrium carbon pools are comparable with Adams (1997). At the end of the spin-up phase a clearcut is simulated (the turkey oak forest was planted around 1925). The simulation of clearcut was performed following the method published by Thornton et al. (2002) and Tatarinov and Cienciala (2006).

Calibration of the BIOME-BGC deciduous broadleaf forest (DBF) submodel for Čifáre was performed using the approach described in Section 3.2. Effective soil depth and biological nitrogen fixation were estimated using Monte Carlo method utilizing average measured carbon pools for the forest (Table 4.2.1.). The calibration results show that effective soil depth is around 0.5 m for Čifáre. Biological nitrogen fixation is estimated to be around 5×10^{-5} kgN/m^2/year.

Our modelling approach was to use one parameterization with several regional climate model output data in order to estimate the uncertainty in the carbon cycle related scenarios.

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
stem C (kg/m^2)	11.10	11.53	11.89	11.97	12.35	12.56	12.78	12.97	13.21	13.34
leaf C (kg/m^2)	0.13	0.14	0.14	0.14	0.14	0.14	0.14	0.15	0.15	0.15
root C (kg/m^2)	2.11	2.18	2.23	2.24	2.30	2.33	2.36	2.39	2.42	2.44

Table 4.2.1. Estimated carbon pools for the Čifáre forest based on biomass inventories for the period of 1998-2007. Note that stem carbon includes all woody aboveground biomass (stem, bark and branches). Dry matter was estimated based on Somogyi (2008). The carbon content of dry matter used for the calculations was 0.49.

The BIOME-BGC simulations were performed with the same, site specific air pollution data but with different regional climate model output. Fig. 4.2.1. shows the atmospheric CO_2 concentration according to the A1B scenario (Nakicenovic et al., 2000), the estimated nitrogen deposition data (Dentener, 2006), the mean annual temperature and annual precipitation sum based on the different regional climate models for Čifáre. All simulations were performed for the time period of 1925-2100. In order to estimate the effect of air pollution on the carbon cycle model simulations were performed with nitrogen deposition and CO_2 concentration held at the year 2000 level.

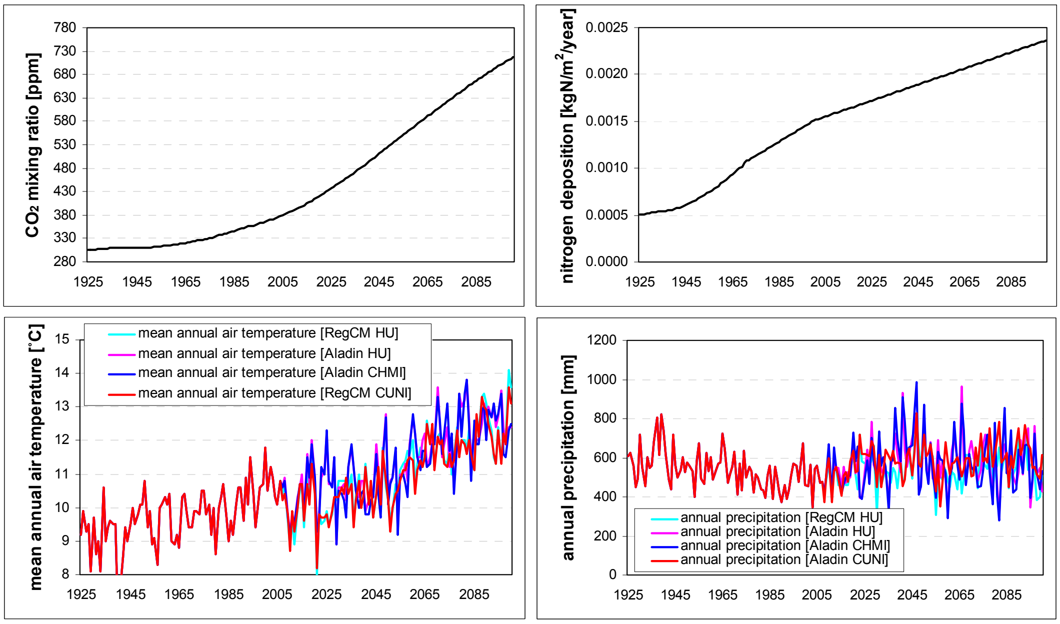

Fig. 4.2.1. Upper left: evolution of the atmospheric CO_2 mixing ratio (1925-2100, A1B scenario). Upper right: evolution of the atmospheric nitrogen deposition (1925-2100). Lower left: mean annual temperature at Čifáre based on the different regional climate models used in the present analysis (1925-2100). Lower right: annual precipitation sum at Čifáre based on the four different regional climate models (1925-2100).

4.3 Integrated assessment of climate change and air pollution impacts on C-cycle in Čifáre forest

We have performed deciduous broadleaf forest specific simulations with the BIOME-BGC model utilizing the methodology described in details in Section 2.2. and Section 4.2. Air pollution impact was taken into account through the CO_2 fertilization effect caused by the increasing atmospheric CO_2 concentration and the increasing nitrogen deposition arising from industrial and agricultural activities. Climate change impact is taken into account with the application of high resolution regional climate model simulation results performed by WP2 of the CECILIA project.

Changes in carbon content of IPCC pools, increments and carbon fluxes with climate change and increasing air pollution

We simulated forest carbon cycle with data derived from 4 different climate models mentioned in Section 2.2. This multi-model analysis helps to estimate the uncertainty of our results.

Fig. 4.2.1. shows the simulated changes in mean annual air temperature, annual precipitation and air pollution. We analysed how the IPCC pools (for the definition of the pools see IPCC, 2003) change due to these impacts. It can be seen in Fig. 4.3.1. that the sizes of these pools are increasing continuously after the relaxation period followed the disturbance (clearcut) event in 1925 (except

leaves, since it is a broadleaved forest), though there are some fluctuations among the years. Increments in carbon content of IPCC pools show a linear tendency except soil pool in which carbon content is increasing more rapidly. Soils generally store carbon for a longer time period than biomass. This carbon sequestration is a benefit as carbon is removed from the atmosphere for a long time.

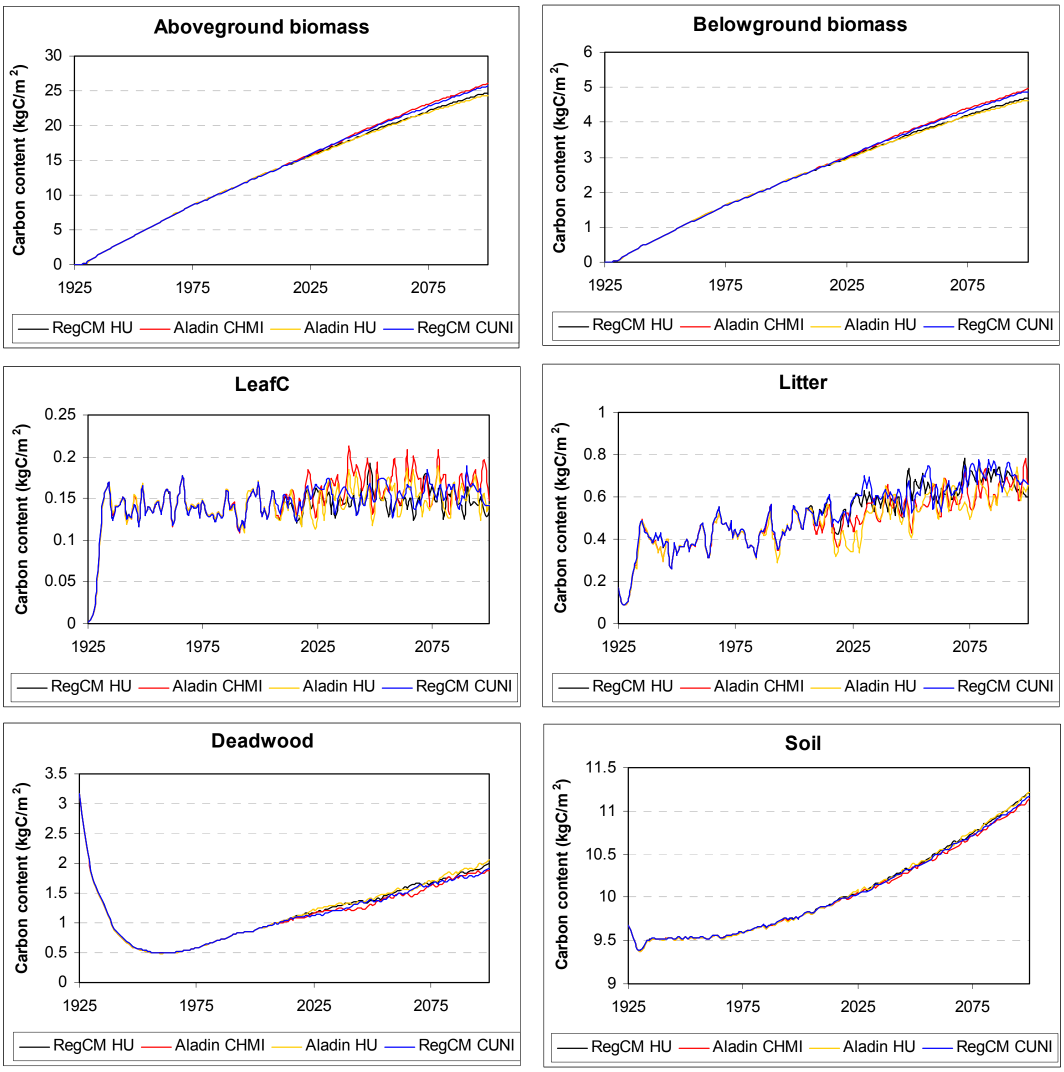

Figure 4.3.1. Simulated evolution of the carbon content of IPCC pools for the Čifáre forest from 1925 to 2100 using the climate data provided by the different regional climate models.

To better understand the connection between development of the forest and environmental change, we studied root and stem increments. A negative tendency was found in both cases (Fig. 4.3.2.). If we compare the average increments of 1971-2000, 2021-2050 and 2071-2100 periods, root increment is 0.029, 0.027 and 0.021 kgC/m^2/yr, while stem increment is 0.15, 0.14 and 0.11 kgC/m^2/yr, respectively.

It can be the impact of climate change but it also can be that increments are age-dependent. To separate these effects, we performed a regression analysis between annual precipitation, mean annual temperature and the increments (Table 4.3.1., Fig. 4.3.3.). Mean annual temperature has a significantly bigger impact on increments than precipitation.

Climate change causes increasing mean annual temperature, so ecosystems are expected to suffer from the elevated temperature. It might be an indicator of a possible positive feedback for climate change: if plants grow slower, they sequester less carbon, which means lower carbon dioxide uptake from the atmosphere. In order to check the validity of this hypothesis we have to investigate the evolution of the ecosystem/atmosphere CO_2 exchange.

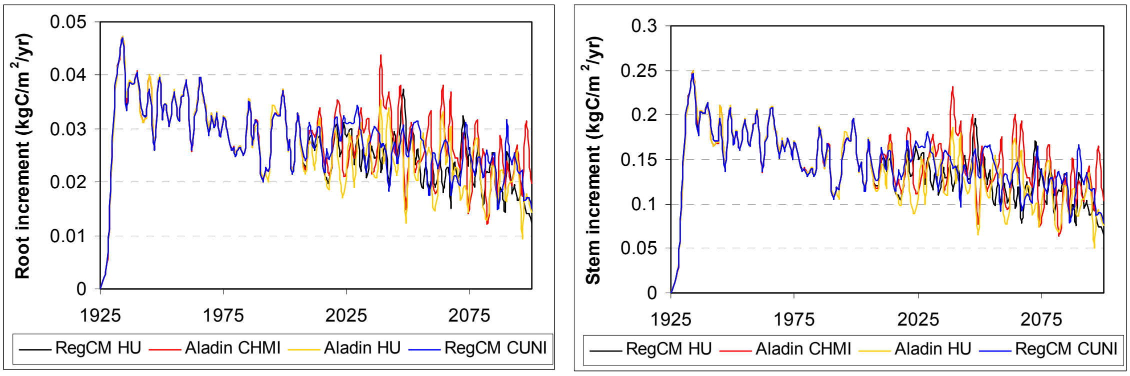

Figure 4.3.2. Simulated evolution of root and stem increment for the Čifáre forest from 1925 to 2100 using the climate data provided by the different regional climate models.

R^2 values	RegCM HU	Aladin CHMI	Aladin HU	RegCM CUNI
precipitation – stem increment	0.141	0.177	0.06	0.052
precipitation – root increment	0.141	0.177	0.06	0.052
temperature – stem increment	0.418	0.398	0.478	0.402
temperature – root increment	0.418	0.399	0.477	0.402

Table 4.3.1. Square of the correlation coefficient (R^2, i.e. explained variance) between annual precipitation, mean annual temperature and carbon pool increments based on the different regional climate model outputs.

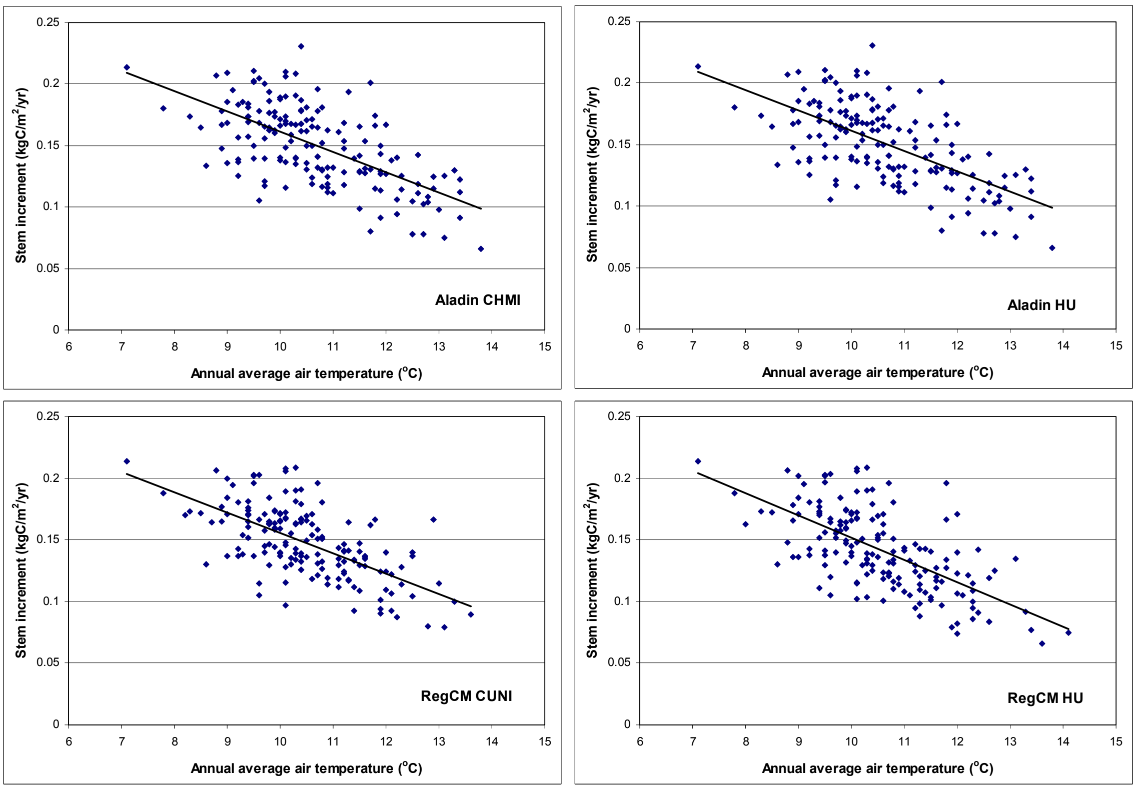

Figure 4.3.3. Relationship between stem increment and annual average air temperature based on the different regional climate models (1925-2100).

An ecosystem's carbon balance is frequently described with the main carbon fluxes of the ecosystem from the point of view of the atmosphere. The main carbon cycle components of an undisturbed forest ecosystem are described in Section 3.3. We investigated the evolution of GPP, Reco and NEE of Čifáre forest based on the model simulations.

Changes in the biosphere/atmosphere carbon fluxes in an unmanaged ecosystem show the response of the ecosystem to climate change and air pollution. Fig. 4.3.4. shows the evolution of the main carbon cycle components between the Čifáre forest and the atmosphere. Different models estimate different fluctuations of carbon fluxes but the tendencies are the same. GPP has a decreasing tendency after 2000 (i.e. more carbon uptake from the atmosphere indicated by the more negative GPP). We can see the increasing magnitude of carbon uptake from the multimodel averages for 1971-2000, 2021-2050 and 2071-2100, which are -973, -1109 and -1172 gC/m^2/yr, respectively.

Total ecosystem respiration (Reco) – which includes autotrophic and heterotrophic respiration – is increasing parallel to GPP but with smaller fluctuations. Increasing tendency can be seen from the averages for the periods 1971-2000, 2021-2050 and 2071-2100, which are 773, 917 and 1009 gC/m^2/yr, respectively.

NEE is the small net balance calculated as GPP+Reco. At Čifáre forest, NEE shows a slightly increasing tendency (it becomes less negative, which means less carbon uptake in the future). In the periods 1971-2000, 2021-2050 and 2071-2100, multimodel NEE averages are -200, -192 and -163 gC/m^2/yr, respectively. NEE has exceeded zero only once in the model simulations: it was 1.9 gC/m^2/yr, calculated by RegCM CUNI model output (minimum NEE was -418 gC/m^2/yr, calculated by Aladin CHMI model output). According to our simulations we conclude that this temperate deciduous broadleaved forest will most likely remain a net sink for atmospheric carbon in the future. Although NEE does not exceed zero (except in one case) increasing NEE may cause a positive feedback for the climate change. The lower carbon uptake might increase the atmospheric carbon dioxide concentration (relative to the possibly unchanged climate when carbon sequestration is stronger) strengthening the greenhouse effect of the atmosphere, and consequently global warming.

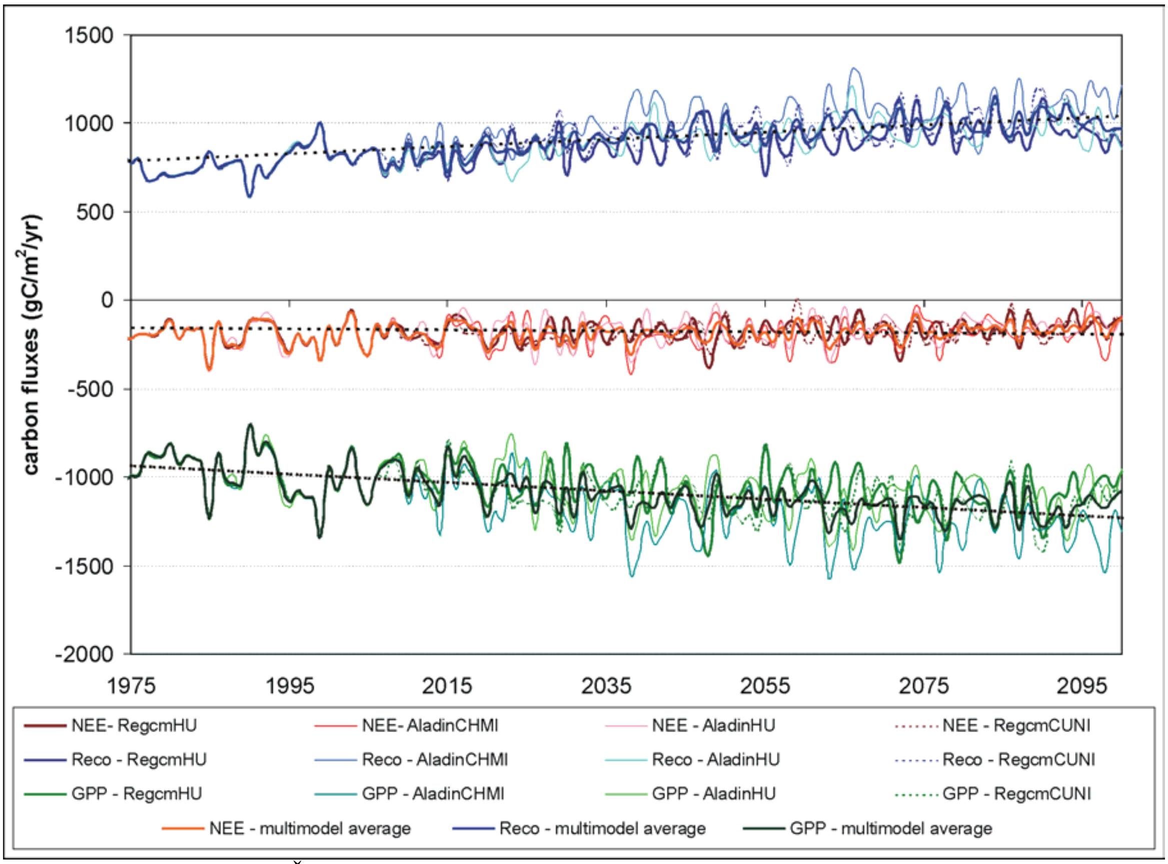

Figure 4.3.4. Changes in Čifáre forest carbon fluxes between 1975 and 2100 using different climate model scenarios. Negative values indicate biospheric carbon dioxide uptake by the vegetation from the point of view of the atmosphere. Dotted lines indicate trend lines fitted to the multimodel average fluxes.

Impact of air pollution

To analyse the impact of air pollution we created four different scenarios within each climate model output simulation: 1) elevated atmospheric CO_2 concentration and N deposition (baseline), 2) CO_2 concentration held at the 2000 year level (FC), 3) N-deposition held at the 2000 year level (FN), 4) CO_2 concentration and N-deposition held at the 2000 year level (FN-FC). For detailed scenario description see Section 2.2.

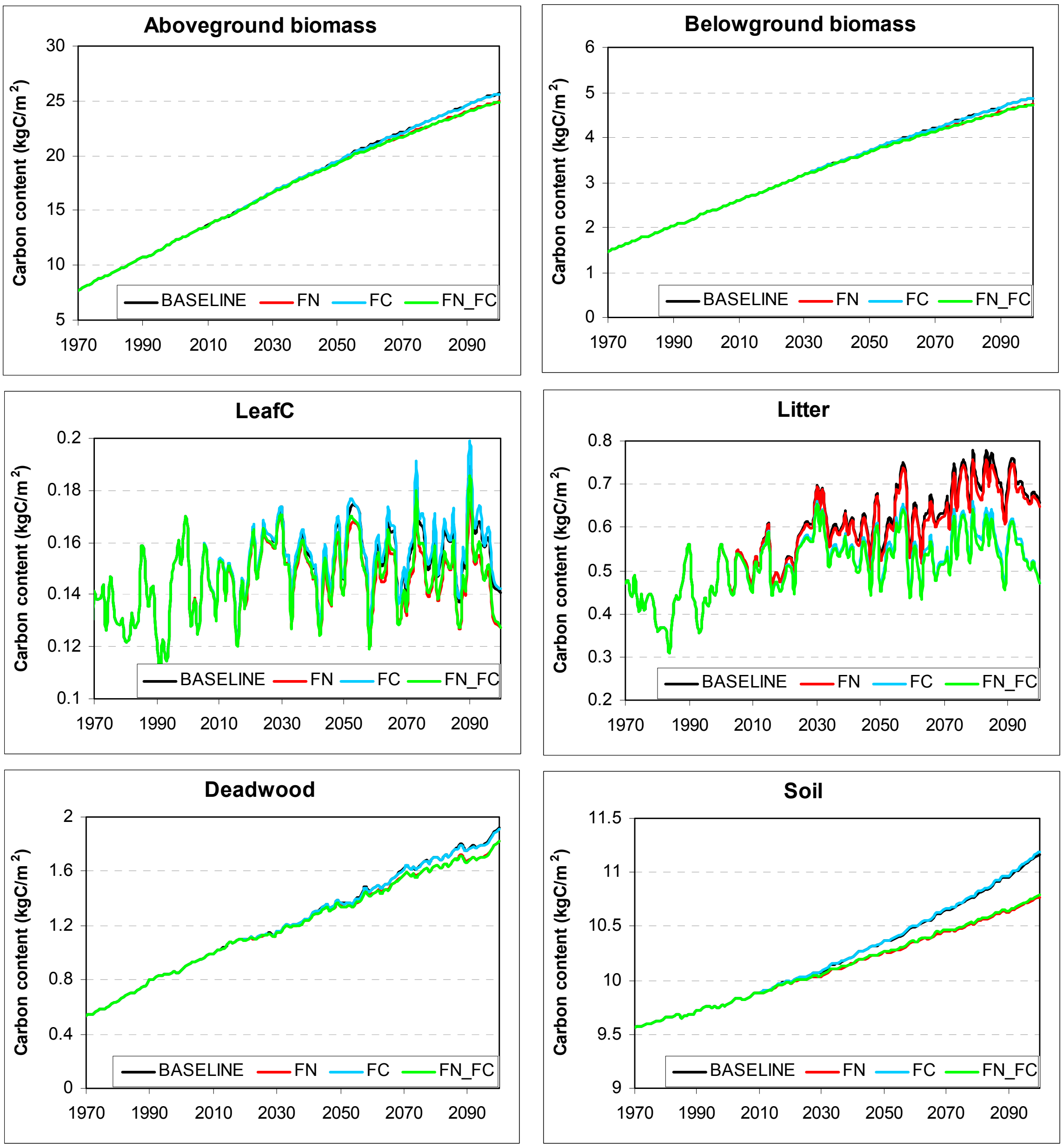

Figure 4.3.5. Changes in carbon content of IPCC pools during 1971-2100 using RegCM CUNI model output and different air pollution scenarios (baseline: elevated atmospheric CO_2-concentration and N-deposition; FC: CO_2-concentration fixed at year 2000 level; FN: N-deposition fixed at year 2000 level; FN-FC: CO_2-concentration and N-deposition fixed at year 2000 level). Other model outputs showed very similar results.

For almost every IPCC pools, FN scenario showed bigger difference as FC relative to baseline (Fig. 4.3.5.). It means that elevated N-fertilization has bigger impact on these pools than elevated atmospheric CO_2-concentration. Evolution of IPCC pools in case of fixed CO_2-concentration is similar to baseline in almost every IPCC pool: biomass growth and turnover, and thus the soil carbon content are increasing. In case of litter, elevated CO_2-concentration has bigger impact on this pool.

N-deposition has a positive effect on biomass growth and turnover. The amount of available reactive N in the soil can be limited for plants. In case of increased N-fertilization, plants can grow rapidly and are able to uptake more CO_2 from the atmosphere (Magnani et al., 2007).

Climate model	Root increment (kgC/m²/yr)				Stem increment (kgC/m²/yr)			
	BASE	FC	FN	FN-FC	BASE	FC	FN	FN-FC
RegCM HU	0.0237	0.0235	0.0223	0.0222	0.125	0.124	0.117	0.117
Aladin HU	0.0230	0.0227	0.0217	0.0217	0.121	0.119	0.114	0.114
Aladin CHMI	0.0262	0.0262	0.0247	0.0248	0.138	0.138	0.130	0.130
RegCM CUNI	0.0256	0.0255	0.0242	0.0241	0.135	0.134	0.127	0.127
Average	**0.0246**	**0.0245**	**0.0232**	**0.0232**	**0.1298**	**0.1288**	**0.1220**	**0.1220**
SD	**0.0015**	**0.0016**	**0.0015**	**0.0015**	**0.0081**	**0.0088**	**0.0077**	**0.0077**

Table 4.3.2. Average carbon pool increments for the period after 2000 based on the different air pollution scenarios. BASE: baseline scenario, elevated atmospheric CO_2-concentration and N-deposition; FC: CO_2-concentration fixed at year 2000 level; FN: N-deposition fixed at year 2000 level; FN-FC: CO_2-concentration and N-deposition fixed at year 2000 level. SD: standard deviation.

Considering carbon pool increments, we can see similar tendencies as for the IPCC pools. The results of FN scenario are close to baseline, while the results of FC scenario are close to the FN-FC (Table 4.3.2.). It means that elevated N-deposition has a bigger impact on increments than elevated CO_2-concentration. Elevated CO_2-concentration has nearly no impact on biomass increments relative to N-pollution.

Climate model	GPP (gC/m²/yr)				Reco (gC/m²/yr)			
	BASE	FC	FN	FN-FC	BASE	FC	FN	FN-FC
RegCM HU	-1067	-1063	-1022	-1019	893	893	862	863
Aladin HU	-1082	-1071	-1041	-1040	912	907	884	886
Aladin CHMI	-1189	-1187	-1141	-1141	1000	1000	967	968
RegCM CUNI	-1116	-1114	-1073	-1070	931	931	901	901
Average	**-1114**	**-1109**	**-1069**	**-1068**	**934**	**933**	**904**	**905**
SD	**54.4**	**56.8**	**52.3**	**53.3**	**46.7**	**47.5**	**45.2**	**45.1**

Climate model	NEE (gC/m²/yr)			
	BASE	FC	FN	FN-FC
RegCM HU	-174	-170	-160	-157
Aladin HU	-170	-164	-157	-154
AladinCHMI	-189	-187	-174	-173
RegCM CUNI	-186	-183	-171	-169
Average	**-180**	**-176**	**-166**	**-163**
SD	**9.2**	**10.8**	**8.3**	**9.2**

Table 4.3.3. Average carbon fluxes for the period after 2000. BASE: baseline scenario, elevated atmospheric CO_2-concentration and N-deposition, FC: CO_2-concentration fixed at year 2000 level; FN: N-deposition fixed at year 2000 level; FN-FC: CO_2-concentration and N-deposition fixed at year 2000 level. SD: standard deviation.

In case of biosphere/atmosphere carbon dioxide exchange, we can see the same tendencies as for the IPCC pools and increments (Table 4.3.3.). FC values are near baseline, and FN values are near FN-FC scenario. Bigger impact of N-fertilization can be observed here also. Average NEE remains lower than zero in all cases which means that vegetation will be net carbon sink in all air pollution scenarios. NEE is higher (less negative, which means less carbon uptake) in case of lower air pollution (FN-FC) scenario. Observing all our model simulations, we found that NEE exceeds zero only once in case of Baseline scenario (high air pollution), 5 times in case of FC scenario, 8 times in case of FN scenario and also 8 times in case of FN-FC (lowest air pollution) scenario.

Based on the results we can conclude that increasing nitrogen deposition has a significant impact on the forest carbon cycle: N stimulates the growth of plants so they can take up more CO_2 from the atmosphere. This reduces the positive feedback caused by increasing mean annual temperature.

5. Hegyhátsál agricultural region - Hungary

5.1 Site description

Hegyhátsál is a small village in the western part of Hungary, in Vas county. Hegyhátsál was selected as a target region for the agricultural related carbon cycle analysis because of the existence of tall tower based measurements there. Since 1997 the carbon dioxide exchange between the biosphere and the atmosphere has been measured on the television/radio transmitter tower owned by Antenna Hungária Corp. at 82 m height (Haszpra et al., 2001; 2005). In this measurement programme we use the so-called eddy covariance technique (Baldocchi, 2003) to calculate the amount of carbon taken up or released by the vegetation in hourly, daily, monthly and annual time step. The measurement is representative to the carbon dynamics of the mixed agricultural region around the tall tower (Haszpra et al., 2005). The tower is surrounded by a regionally typical mixture of agricultural fields (including winter wheat and maize).

During 1999 and 2000 the CO_2 exchange of a managed, semi-natural grassland located around the transmitter tower was also measured at 3 m height (Barcza et al., 2003). This measurement was restarted in autumn, 2006, and it is in operation now.

Since the carbon dynamics of agricultural crops is closely related to their productivity, our simulations may provide insight into the potential changes in crop productivity and food security. Using multiple regional climate models we can estimate the uncertainty of the carbon cycle related simulations. Climate change related studies and estimation of future carbon cycle related trends are of great importance in this region.

5.2 Data and methods

In the present analysis croplands are handled as semi-natural grasslands, or in other words as a kind of "super grass" (i.e. fertilized grass; Vetter et al., 2007; Barcza et al., 2009) using the existing internal grass parameterization of the BIOME-BGC model. In order to provide accurate model results training data is needed since the parameterization can change a lot from site to site (White et al., 2000).

The only monitoring project producing CO_2 net ecosystem exchange (NEE, i.e. the net carbon exchange) data for mixed agricultural fields in Hungary is carried out at Hegyhátsál. The eddy covariance system installed at 82 m elevation above the ground has been providing regional scale NEE data since 1997. The data are used for the calibration of BIOME-BGC (using the grass submodel). Calibration of the BIOME-BGC model was performed with the measured daily eddy covariance data using Monte Carlo Maximum Likelihood (MCML) approach (Hollinger and Richardson, 2005). The calibration was accomplished using nine years of measurement data (1997-1999, 2001-2006). Modeled gross photosynthesis (Gross Primary Production, GPP) explained about 80% of the measured GPP variance (R^2=0.8), while modeled total ecosystem respiration (Reco) explained about 72% of the total variance (R^2=0.72).

Managed grasslands provide fodder that is used to feed animals. It is less known that at present European grasslands act as net carbon sinks thus they take up carbon dioxide from the atmosphere which mitigates climate change (Janssens et al., 2005). If climate change and air pollution will modulate the main carbon flux components this carbon sequestration may vanish that can act as a positive feedback to the warming. The future behavior of the Hegyhátsál grassland is also simulated with BIOME-BGC using its C3 grass submodel.

At Hegyhátsál the grass is regularly cut twice a year. Since the BIOME-BGC model does not handle any management strategies like mowing, we extended the model with this feature. On the mowing days the leaf area index is decreased to a mowing limit (1.2 m^2/m^2). According to this ratio the aboveground biomass is decreased (carbon, nitrogen and water pools), and the cut-down biomass is transported away from the area (does not get into the litter pools).

Since the internal C3 grass parameterization is only appropriate for the unmodified model, we calibrated this extended version of BIOME-BGC. The calibration was performed using the eddy covariance data measured at 3 m elevation around the Hegyhátsál tower (Barcza et al., 2003). As the result of calibration the model explained 78% of the measured GPP, 91% of the measured Reco and 56% of the measured NEE variation.

The agricultural related simulations (mixed cropland and grassland related studies) were performed with the same meteorological and air pollution data. Fig. 5.2.1. shows the ambient CO_2 concentration according to the A1B scenario (Nakicenovic et al., 2000), the estimated nitrogen deposition data (Dentener, 2006), the mean annual temperature and annual precipitation sum based on the different regional climate models. All simulations were performed for the time period of 1971-2100. In order to estimate the effect of air pollution on the carbon cycle model simulations were performed with nitrogen deposition and CO_2 concentration held at the year 2000 level.

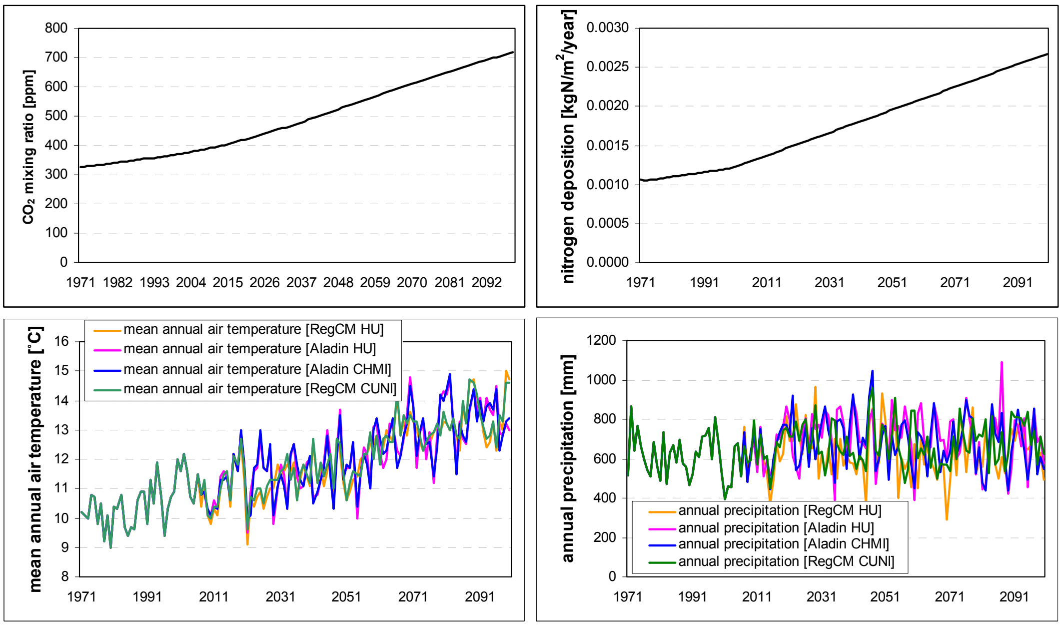

Figure 5.2.1. Upper left: evolution of the atmospheric CO_2 mixing ratio (1971-2100, A1B scenario). Upper right: evolution of the atmospheric nitrogen deposition (1971-2100). Lower left: mean annual temperature at Hegyhátsál based on the different regional climate models used in the present analysis (1971-2100). Lower right: annual precipitation sum at Hegyhátsál based on the different regional climate models (1971-2100).

5.3 Integrated assessment of climate change and air pollution impacts on agricultural C-cycle in Western Hungary

Forests can store a lot of carbon, and it is rather simple to estimate the carbon content of the aboveground biomass using simple allometric measurements. In contrast, in herbaceous ecosystems like croplands or grasslands, aboveground biomass is not the dominant carbon pool as it may diminish from year to year e.g. as a consequence of human intervention (harvest). We need different measures to quantify the cropland related carbon cycle.

Agricultural carbon balance is generally described with the main carbon fluxes of the ecosystem from the point of view of the atmosphere. Carbon uptake from the atmosphere (in the form of CO_2) via photosynthesis is called gross primary production (GPP). Total ecosystem respiration (Reco, the amount of CO_2 that increases the atmospheric CO_2 content) is the sum of respiration of the plant itself (autotrophic respiration, Ra), and respiration of heterotrophs (heterotrophic respiration, Rh). Net primary production (NPP) is the net biological production of the plant, and it is defined here as |GPP+Ra|. Net ecosystem exchange (NEE) is the net carbon balance of the ecosystem if there is no horizontal carbon displacement and it is defined as GPP+Reco. In case of managed ecosystems carbon is transported away from the ecosystem due to harvest or mowing. The removed carbon is generally consumed by humans or animals, and after digestion its carbon content returns the atmosphere typically within a year. This horizontally displaced carbon has to be taken into account when calculating the total carbon balance of an ecosystem. Net biome production (NBP) is the sum of NEE and the removed carbon. The removed carbon has positive sign as it is associated with respiration.

In the present study negative values indicate CO_2 (or carbon) removal from the atmosphere, while a positive value marks CO_2 (or carbon) loss from the ecosystem. For example, negative NEE means net carbon uptake by the vegetation from the point of view of the atmosphere; negative NBP means carbon accumulation at the ecosystem scale. The exception is NPP where carbon accumulation is described as positive (NPP can not be negative).

5.3.1 Managed grass

We have performed grassland specific simulations with the BIOME-BGC model using the methodology described in Section 2.2. Air pollution impact was taken into account through the CO_2 fertilization effect caused by the increasing CO_2 concentration of the atmosphere and the increasing nitrogen deposition arising from industrial and agricultural activities (Fig. 5.2.1.). Climate change impact is accounted for with the application of high resolution climate model simulation results performed by WP2 of the CECILIA project (Section 2.2).

The changes of the main carbon cycle components of the managed grassland at Hegyhátsál based on the regional climate model results can be seen on Fig. 5.3.1.1. The magnitude of the annual sums and variations of respiration and gross primary production will increase during the examined period (1971-2100). The magnitude of annual net ecosystem exchange will increase which means that carbon uptake will increase. The vegetation will remain net sink in most of the years in the simulation period from the point of view of the atmosphere

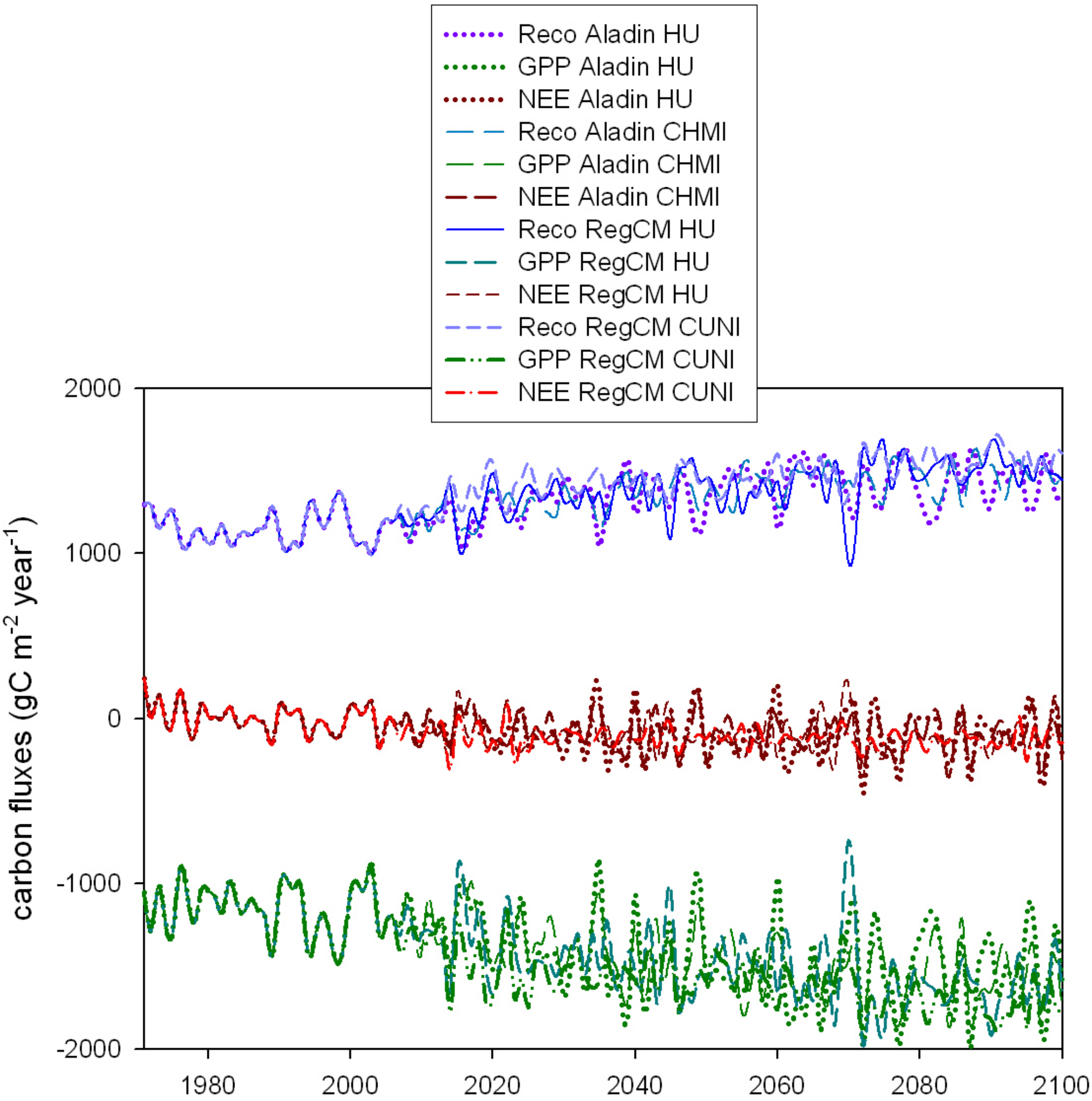

Figure 5.3.1.1. Changes in the managed grass carbon fluxes between 1971 and 2100 using different climate model scenarios. Air pollution causes increasing CO_2 concentration and increasing nitrogen deposition. Negative values indicate CO_2 uptake from the atmosphere.

Fig. 5.3.1.2. shows the changes in the mean annual courses of the main carbon cycle components in future periods (left: 2021-2050; right: 2071-2100) relative to the reference mean annual course (1971-2000). Significant changes will happen at the beginning of the year (dormant period) and in the middle of the vegetation period in every carbon cycle components and in both periods: carbon components will start increasing earlier, will reach their maximum values earlier and these maximum values will be higher (in absolute sense). The increase in carbon fluxes in the dormant period is higher using RegCM HU and RegCM CUNI models; the increase in the vegetation period is higher using Aladin HU and Aladin CHMI models. The changes (relative to the reference period) will be higher in 2071-2100, especially in the case of Aladin CHMI model. As we mentioned earlier, for every carbon cycle simulation business-as-usual management is assumed, which means two mowing in every year (yearday 150 and 234). The carbon loss effect of mowing can be seen on each course.

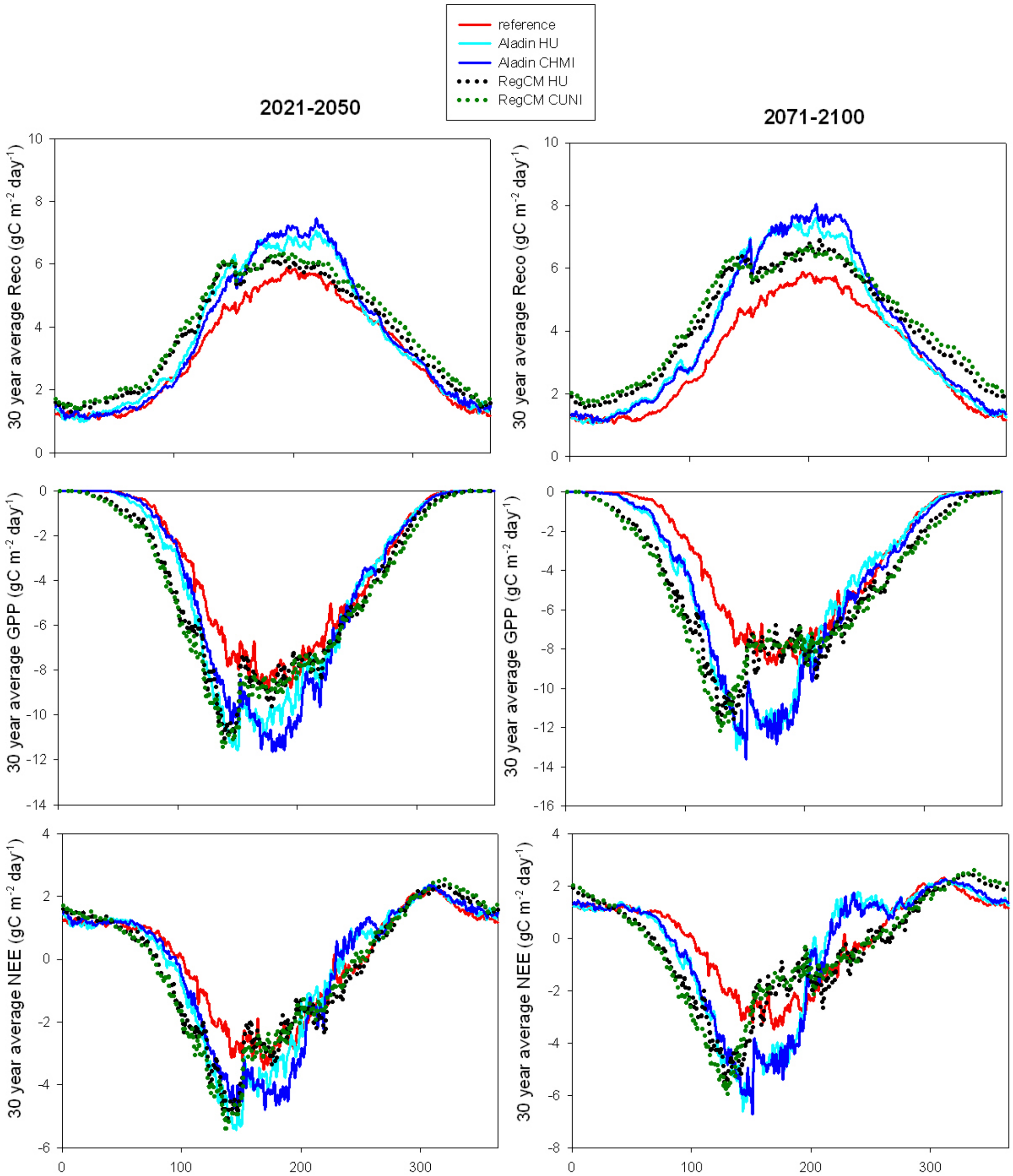

Figure 5.3.1.2. Effect of air pollution and climate change on the estimated mean annual courses of Reco, GPP and NEE during 2021-2050 (left), 2071-2100 (right) and the reference course (reference period: 1971-2000). The sharp changes around day 150 are caused by the harvest of the grass. Negative values indicate carbon uptake from the atmosphere, while positive values indicate carbon release.

In order to estimate the effect of climate change and air pollution on the carbon cycle of the grassland, the different effects has to be examined separately.

First we see the model results with climate data from RegCM HU model. In Fig. 5.3.1.3. a) and b) the difference between the mean annual courses of the carbon cycle components with fixed N deposition after year 2000 (FN) relative to the increasing air pollution course can be seen (BASELINE; air pollution causes both increasing CO_2 concentration and both increasing nitrogen deposition). Fig. 5.3.1.3. c) and d) show the difference between the mean annual courses of the carbon cycle components with fixed CO_2 concentration after year 2000 (FC) relative to the BASELINE. If the difference is positive, it means that BASELINE course is lower than the fixed ones, therefore the increasing N deposition or CO_2 concentration causes decrease in carbon cycle components in absolute sense (relative to the fixed case) and vice versa. It means that Reco will be higher and GPP and NEE will be lower for BASELINE scenario than using reference data (lower GPP means higher gross carbon uptake; lower NEE means higher net carbon uptake), so increasing N deposition and CO_2 concentration will increase carbon uptake.

Examining the effect of increasing N deposition (FN-BASELINE: difference between FN and BASELINE) in Fig. 5.3.1.3. a) and b) it can be seen that significant changes will happen only in the middle growing season: decrease in Reco and increase in NEE and GPP difference courses. It means that Reco will be higher and GPP and NEE will be lower for BASELINE scenario than for FN scenario, so increasing N deposition will increase Reco and decrease GPP and NEE. Since the decrease in GPP (lower GPP means higher gross carbon uptake) is higher than the increase in Reco, NEE will decrease (more negative NEE means higher net carbon uptake), so increasing N deposition will increase carbon-fixing. This effect is valid for both periods (2021-2050 and 2071-2100), but with higher rates in the second one.

On Fig. 5.3.1.3. c) and d) we can see the effect of increasing CO_2 concentration (FC-BASELINE: difference between FC and BASELINE). The picture is similar as in the case of FN-BASELINE, but with bigger changes in Reco, GPP and NEE courses in both periods and the changes can be observed in the early growing season too.

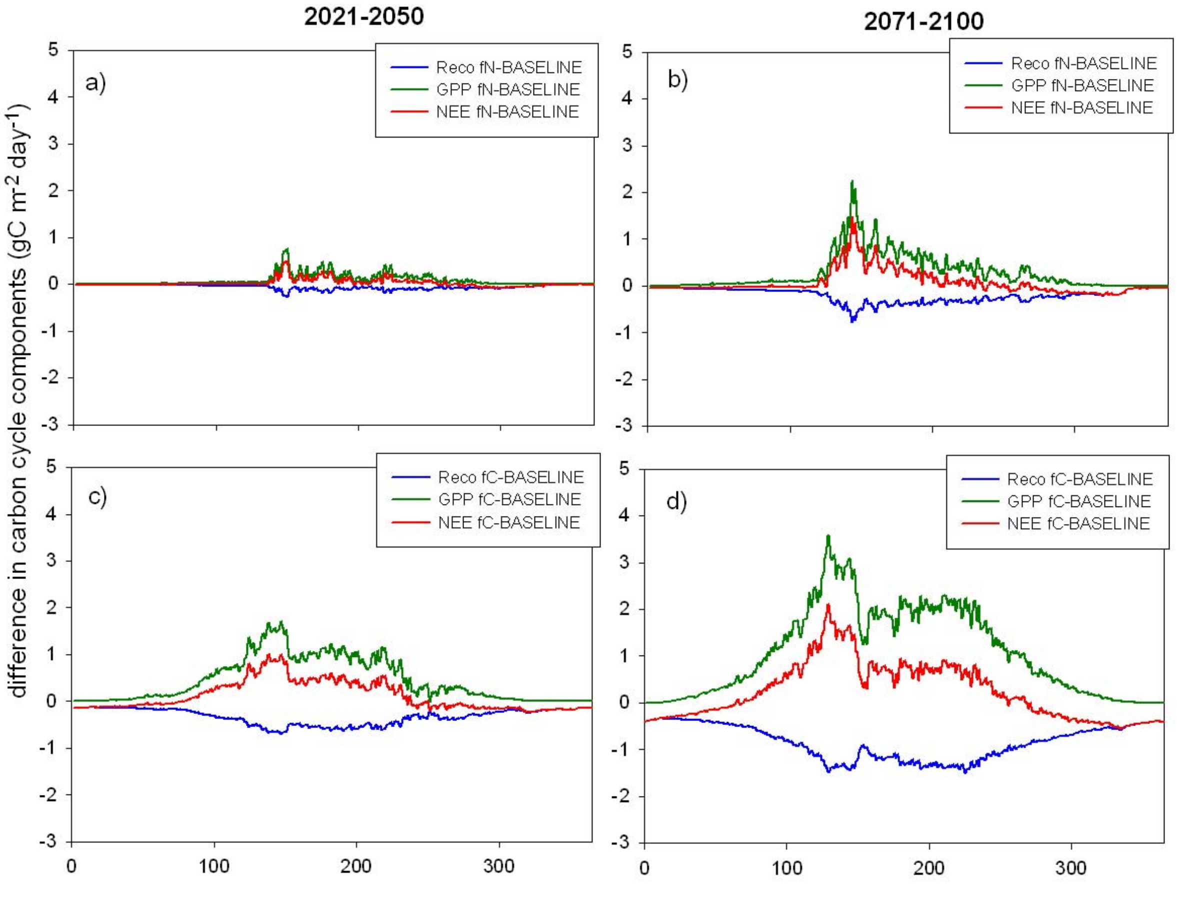

Figure 5.3.1.3. Effect of the increasing nitrogen deposition and CO_2 concentration on the estimated difference between the mean annual courses of Reco, GPP and NEE with climate data from RegCM HU. a) and b) show the difference between carbon cycle components course using FN and BASELINE scenario (FN-BASELINE) in simulation period 2021-2050 (left) and 2071-2100 (right). c) and d) show the difference between carbon cycle components course using FC and BASELINE scenario (FC-BASELINE) in simulation period 2021-2050 (left) and 2071-2100 (right).

The next step is to examine the model results using climate data from RegCM CUNI model. In Fig. 5.3.1.4. a) and b) the difference between the mean annual courses of the carbon cycle components with fixed N deposition after year 2000 (FN) relative to the increasing air pollution course can be seen (BASELINE; air pollution causes both increasing CO_2 concentration and increasing nitrogen deposition). Fig. 5.3.1.4. c) and d) show the difference between the mean annual courses of the carbon cycle components with fixed CO_2 concentration after year 2000 (FC) relative to the BASELINE.

Examining the effect of increasing N deposition (FN-BASELINE: difference between FN and BASELINE) in Fig. 5.3.1.3. a) and b) it can be seen that the changes are quite similar to those estimated using RegCM HU model (Fig. 5.3.1.3.).

On Fig. 5.3.1.4. c) and d) we can see the effect of increasing CO_2 concentration (FC-BASELINE: difference between FC and BASELINE). Significant changes will happen in the early growing season: decrease in Reco and increase in NEE and GPP difference courses (the effect is similar to the case of FN-BASELINE). In the middle of the growing season the Reco difference is positive, GPP difference is negative which means that Reco will be lower and GPP will be higher for BASELINE scenario than for FN scenario. It means that in this period increasing CO_2 concentration will decrease carbon-fixing and respiration. In the late growing season the picture is similar as in the early growing season: increasing CO_2 concentration will increase carbon-fixing and respiration. We see a similar picture in the second simulation period (2071-2100) in the early growing season and the dormant period, but with bigger changes in Reco, GPP and NEE courses. In the middle of the growing season the differences between carbon fluxes using FC and BASELINE scenario is close to zero, which means that in this period the increasing CO_2 concentration will not affect to the carbon fluxes.

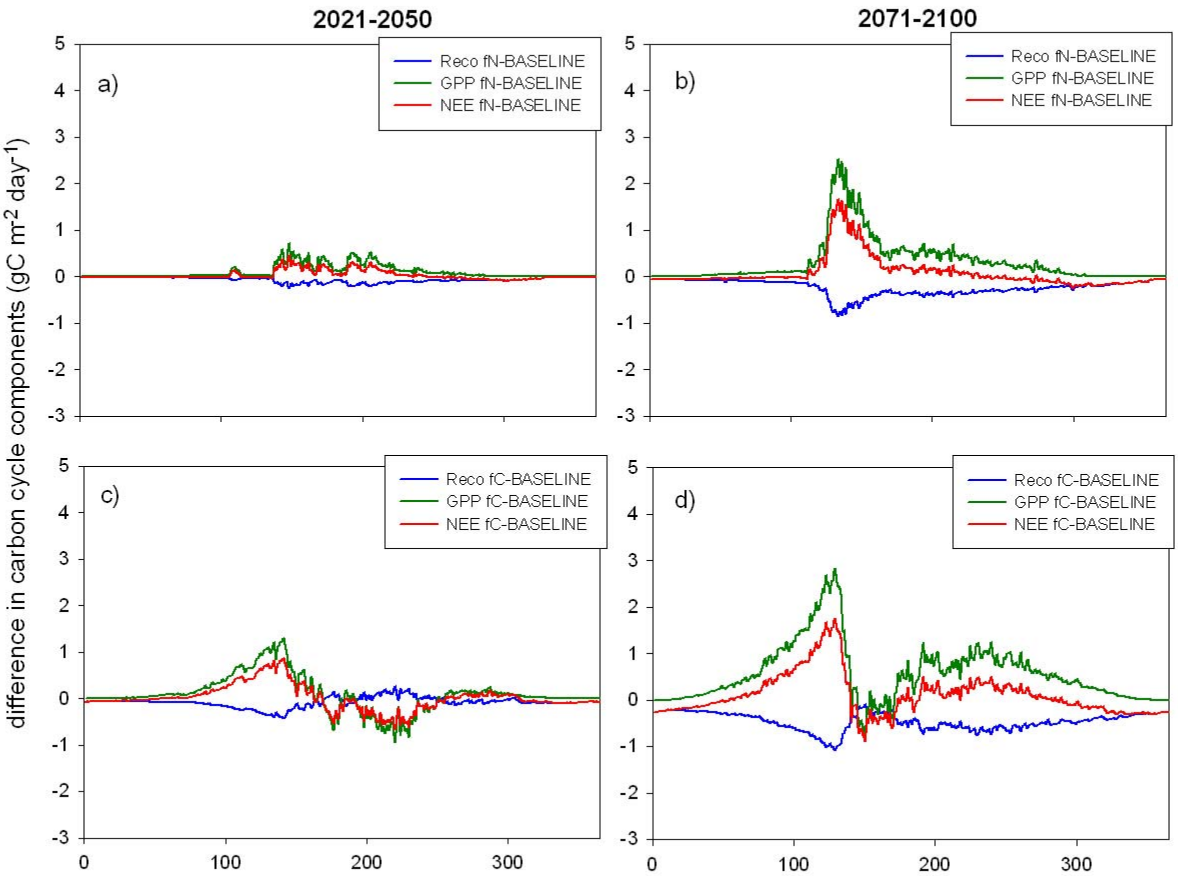

Figure 5.3.1.4. Effect of the increasing nitrogen deposition and CO_2 concentration on the estimated difference between the mean annual courses of Reco, GPP and NEE with climate data from RegCM CUNI. a) and b) show the difference between carbon cycle components course using FN and BASELINE scenario (FN-BASELINE) in simulation period 2021-2050 (left) and 2071-2100 (right). c) and d) show the difference between carbon cycle components course using FC and BASELINE scenario (FC-BASELINE) in simulation period 2021-2050 (left) and 2071-2100 (right).

In Fig. 5.3.1.5. a) and b) we can see the difference between the FN mean annual carbon cycle components relative to BASELINE scenario with climate data from the Aladin HU model. Fig. 5.3.1.5. c) and d) show the difference between the FC mean annual carbon cycle components relative to BASELINE scenario again with climate data from the Aladin HU model.

Examining simulation results using Aladin HU climate data and FN-BASELINE scenario the picture (Fig. 5.3.1.5 a)) shows an interesting result: no significant difference can be seen between carbon courses for FN and BASELINE scenario using Aladin HU data, which means that the increasing N deposition has only slight effect on carbon components in 2021-2050. In contrast, in the second period (2071-2100; Fig. 5.3.1.5 b)) the effect of the increasing N deposition will appear: in the whole vegetation period decrease will happen in Reco and increase in NEE and GPP difference courses. It means that Reco will be higher and GPP and NEE will be lower for BASELINE scenario than for FN scenario, so increasing N deposition will increase Reco and decrease GPP. Since the decrease in GPP (lower GPP means higher gross carbon uptake) is higher than the increase in Reco, NEE will decrease (lower NEE means higher net carbon uptake), so increasing N deposition will increase carbon-fixing.

Comparing the model results from RegCM HU and Aladin HU we can see, that the results are similar in case of FC-BASELINE (Fig. 5.3.1.5 c) and d)), but with higher rates of the changes in Reco, GPP and NEE courses.

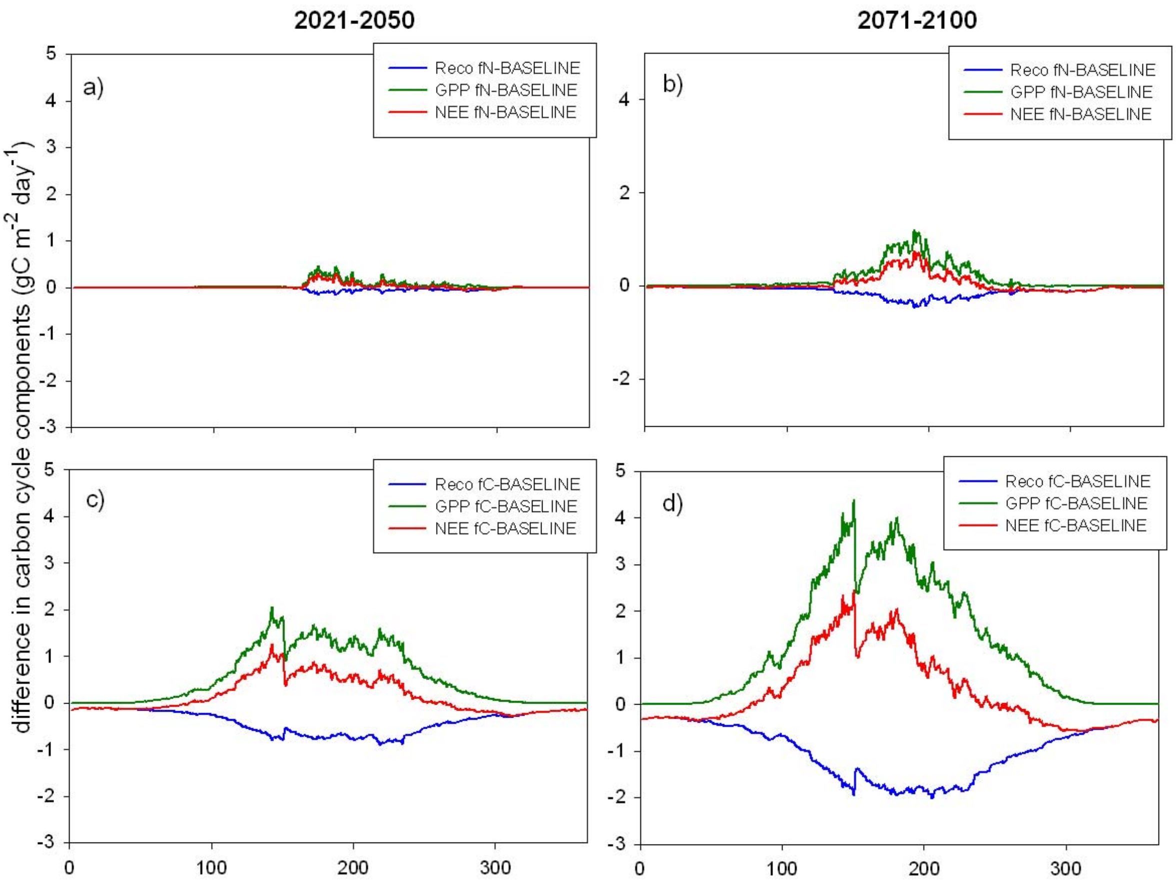

Figure 5.3.1.5. Effect of the increasing nitrogen deposition and CO_2 concentration on the estimated difference between the mean annual courses of Reco, GPP and NEE with climate data from Aladin HU. a) and b) show the difference between carbon cycle components course using FN and BASELINE scenario in simulation period 2021-2050 (left) and 2071-2100 (right). c) and d) show the difference between carbon cycle components course using FC and BASELINE scenario in simulation period 2021-2050 (left) and 2071-2100 (right).

In Fig. 5.3.1.6. a) and b) we can see the difference between the FN mean annual carbon cycle components relative to BASELINE scenario with climate data from the Aladin CHMI model. Fig.

5.3.1.6. c) and d) show the difference between the FC mean annual carbon cycle components relative to BASELINE scenario again with climate data from the Aladin CHMI model.

Comparing the model results from Aladin HU and Aladin CHMI we can see, that the results are very similar in case of FN-BASELINE (Fig. 5.3.1.5 a) and b) and Fig. 5.3.1.6 a) and b)) and in case of FC-BASELINE (Fig. 5.3.1.5 c) and d) and Fig. 5.3.1.6 c) and d)) but with lower rates of the changes in Reco, GPP and NEE courses.

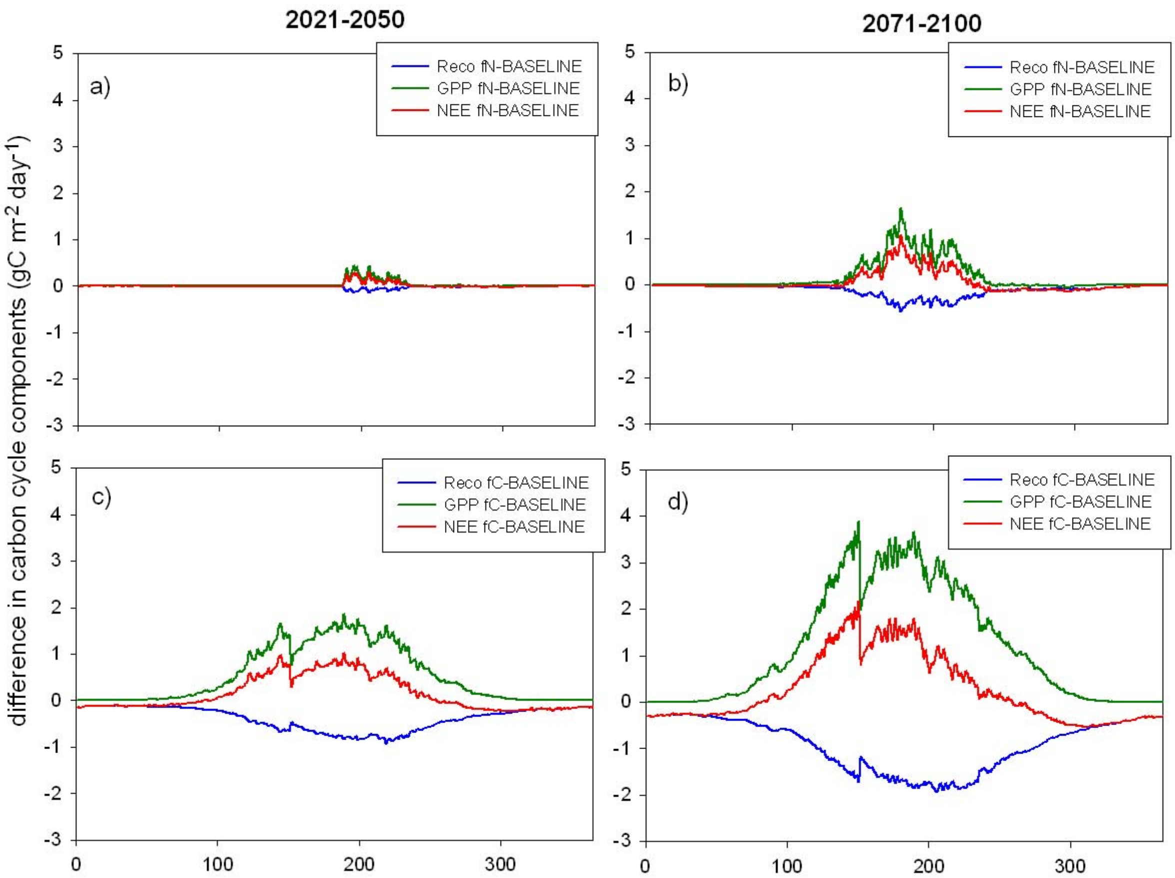

Figure 5.3.1.6. Effect of the increasing nitrogen deposition and CO_2 concentration on the estimated difference between the mean annual courses of Reco, GPP and NEE with climate data from Aladin CHMI. a) and b) show the difference between carbon cycle components course using FN and BASELINE scenario in simulation period 2021-2050 (left) and 2071-2100 (right). c) and d) show the difference between carbon cycle components course using FC and BASELINE scenario in simulation period 2021-2050 (left) and 2071-2100 (right).

Fig. 5.3.1.7 shows the evolution of the carbon pools of the managed (left) and the unmanaged (right) grassland during 1971-2100. Since the results regarding to the difference between unmanaged and managed grassland are similar using different climate model data, only the results using Aladin HU climate data are presented. Carbon content of the vegetation will increase for both managed and unmanaged grassland with BASELINE and FN scenarios, but with fixed CO_2 concentration it will decrease in the second part of the examined period. According to our expectations the increase in vegetation is bigger in case of unmanaged scenario, because mowing causes loss in the carbon content of the vegetation.

Carbon content of the soil will decrease for both managed and unmanaged grassland at the beginning of the scenarios. However, in case of unmanaged grassland the soil carbon stops decreasing and start increasing after 2020. So the most important effect of mowing is the constant decrease of the soil carbon and therefore the total carbon content of the ecosystem (since most of the changes in total carbon comes from changes of the soil carbon, their changes are very similar). The loss is the smallest for the BASELINE scenario and the largest for FC scenario, which means that the increasing CO_2 concentration (and in less extent the increasing N deposition) can compensate a certain part of the carbon loss caused by mowing.

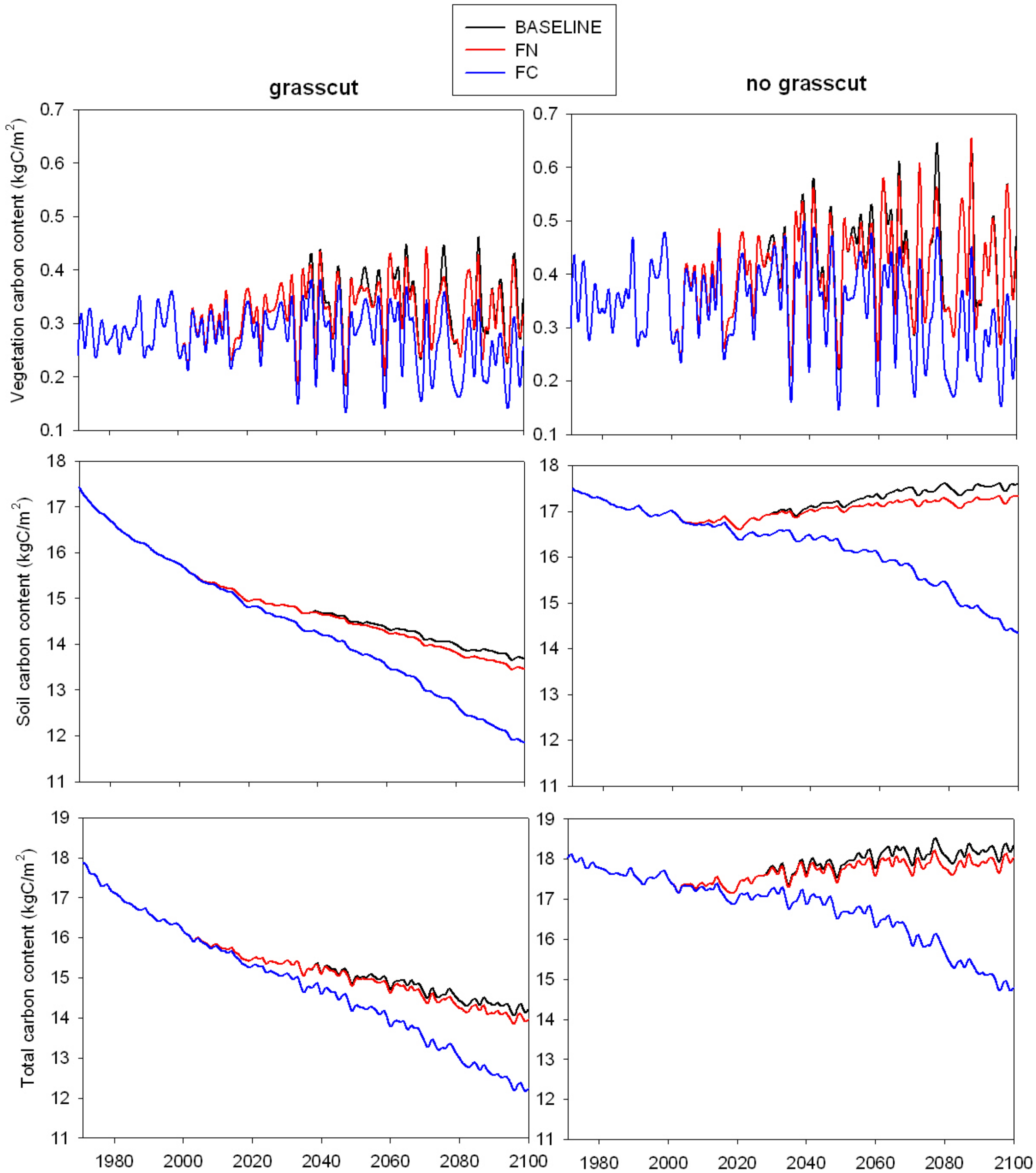

Figure 5.3.1.7. Changes in the managed (left) and unmanaged (right) ecosystem carbon pools during 1971-2100 using different air pollution scenarios (BASELINE, FC, FN).

Fig.5.3.1.8 shows the evaluation of the total carbon content of the managed grassland using the different climate model data (Aladin HU; Aladin CHMI; RegCM HU; RegCM CUNI) and different air pollution scenarios (BASELINE, FC, FN). Total carbon content will decrease for all models and for both of the scenarios, but the decrease is the biggest using FC scenario and Aladin HU model, while it is the smallest using BASELINE scenario and RegCM CUNI model. This means that the increasing air pollution (mainly the increasing CO_2 concentration) can mitigate the carbon loss of the ecosystem caused by management (mowing).

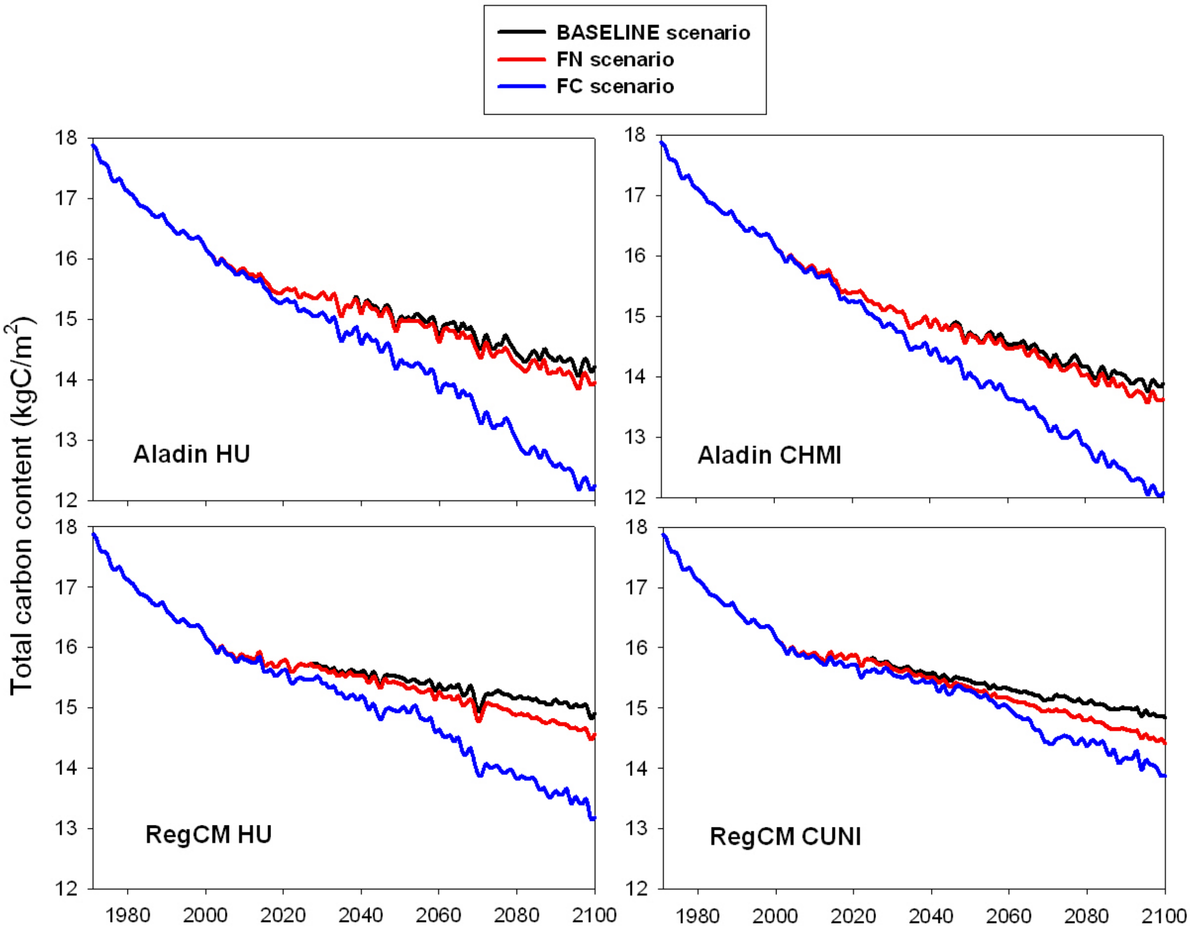

Figure 5.3.1.8. Changes in the total ecosystem carbon content during 1971 and 2100 using different climate model data (Aladin HU; Aladin CHMI; RegCM HU; RegCM CUNI) and different air pollution scenarios (BASELINE, FC, FN).

Fig. 5.3.1.9 shows the evolution of the net biome production (NBP) of the managed grassland using different climate model data and different air pollution scenarios (BASELINE, FC, FN). In our case net biome production is the sum of net ecosystem exchange (NEE) and the carbon loss from mowing. NEE has negative sign if the ecosystem is net sink and it has positive sign if it is net source. Since the mowed and horizontally displaced grass returns the atmosphere very soon (typically within a year; Ciais et al., 2007), carbon loss from mowing has positive sign, because it means net surplus to the atmosphere. The amount of mowed grass will increase and NEE will decrease during the examined period. Their sum, i.e. net biome production will slightly decrease for both of the scenarios and for all models. It means that the ecosystem carbon loss will be slower than at present which is in accordance with the evolution of the total carbon content of the ecosystem presented in Fig. 5.3.1.8. Note that when using climate data from Aladin HU and Aladin RegCM models, there are much more years when the ecosystem is net source and the average NBP in the examined period is greater than in case of using RegCM HU and RegCM CUNI models. The courses of NBP are quite similar when using FC and BASELINE scenario; NBP has lower values when using FN scenario. This means that increasing nitrogen deposition increases NBP, or in other words decreases carbon sequestration.

According to the model results the grassland will affect to the CO_2 content of the atmosphere and therefore will cause feedback for global change.

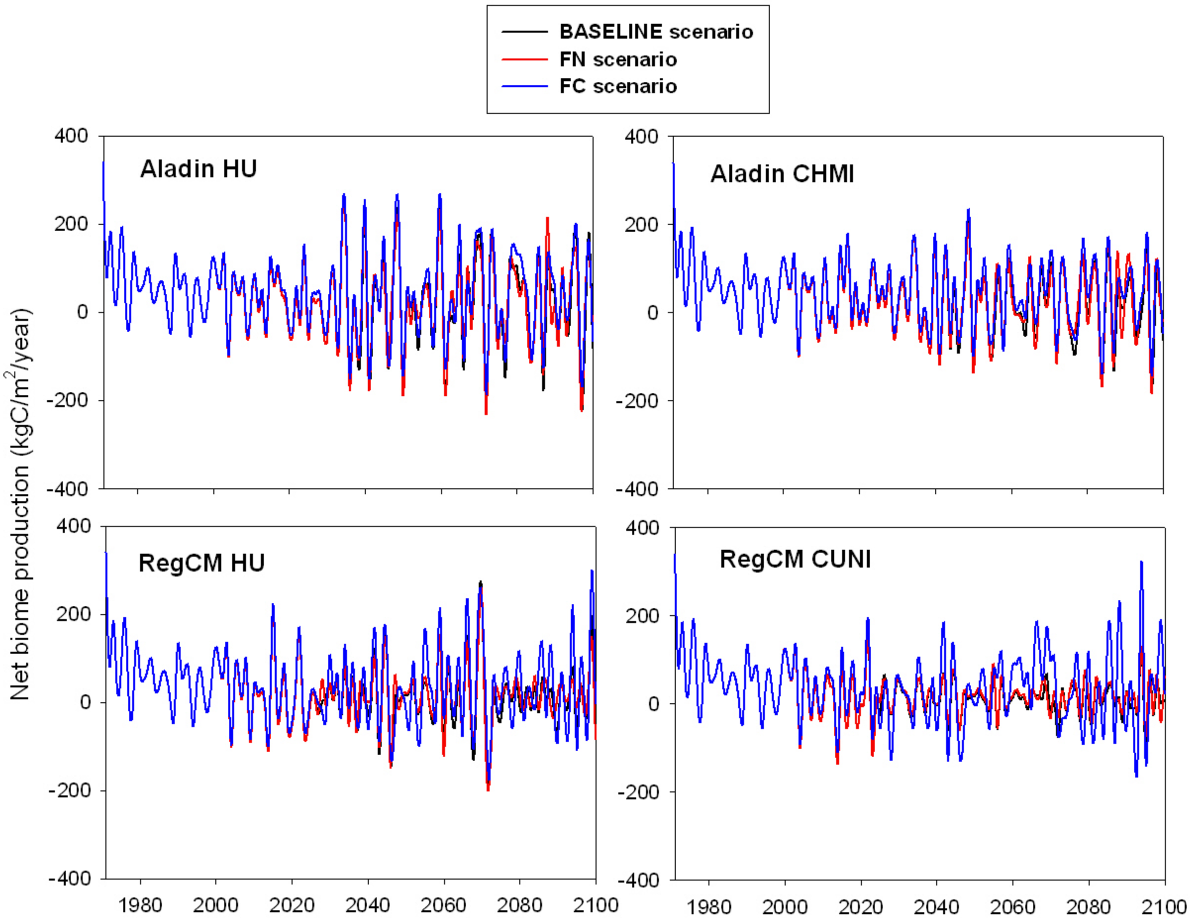

Figure 5.3.1.9. Changes in the net biome production during 1971 and 2100 using different climate model data (Aladin HU; Aladin CHMI; RegCM HU; RegCM CUNI) and different air pollution scenarios scenarios (BASELINE, FC, FN).

5.3.2 Mixed cropland typical for Central Europe

We have performed cropland specific simulations with the BIOME-BGC model using the methodology described in Section 2.2. Air pollution impact was taken into account through the CO_2 fertilization effect caused by the increasing CO_2 concentration of the atmosphere and the increasing nitrogen deposition arising from industrial and agricultural activities (Fig. 5.2.1.). Climate change impact is accounted for with the application of high resolution climate model simulation results performed by WP2 of the CECILIA project.

Fig. 5.3.2.1. shows the modeled evolution of the main carbon cycle components of the mixed cropland at Hegyhátsál based on the regional climate model results. It can be seen that the magnitude of both GPP and Reco increase, while NEE will be essentially unchanged until 2100. It means that while gross carbon uptake and total ecosystem respiration both increase, the net effect of climate change and air pollution on the biospheric carbon balance is not significant. This is of course only true for the biosphere/atmosphere CO_2 exchange from the point of view of the atmosphere. In agricultural production we have to take into account the carbon that is removed from the ecosystem by other processes (erosion, harvest, fire, etc.). If crop yield increases in the future this might change the overall picture for agricultural carbon balance and climate feedback.

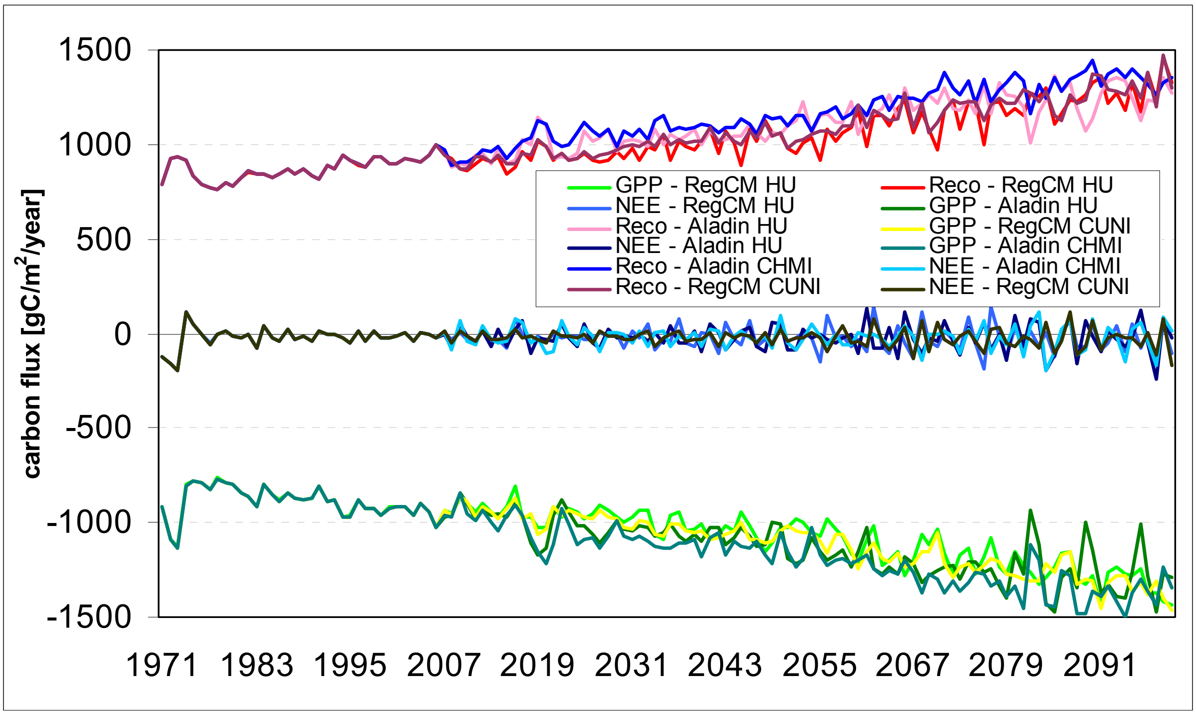

Figure 5.3.2.1. Changes in the agricultural carbon fluxes between 1971 and 2100 using different climate model scenarios. Negative values indicate biospheric carbon dioxide uptake by the vegetation from the point of view of the atmosphere.

NEE is the small balance between two large fluxes of GPP and Reco. In order to estimate the effect of climate change and air pollution on the carbon cycle of the mixed agricultural region, GPP and Reco has to be scrutinized separately. Fig. 5.3.2.2. shows the evolution of GPP and Reco using the 4 possible combinations of changing CO_2 concentration and nitrogen deposition (climate change is considered in all scenarios).

In case of RegCM HU and RegCM CUNI increasing nitrogen deposition explains the difference between the no-air-pollution-increase (NAPI) scenario (N deposition and CO_2 concentration is fixed at their year 2000 value) and the baseline scenario (N deposition and CO_2 concentration are increasing according to Fig. 5.2.1). Note that the magnitude of GPP and Reco increase as a consequence of climate change even in the NAPI scenario.

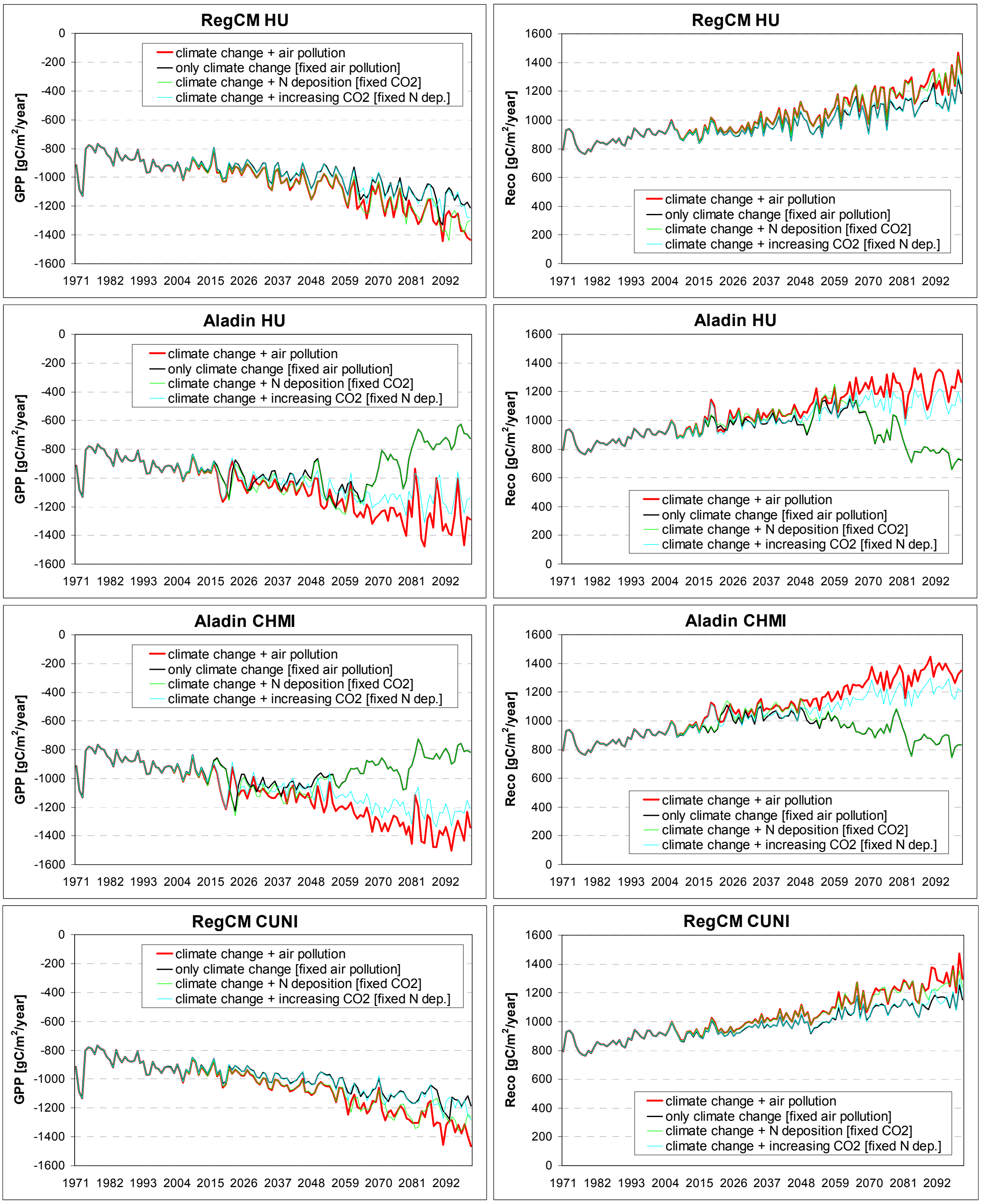

Figure 5.3.2.2. Effect of increasing N deposition and CO_2 concentration on the main carbon fluxes using different regional climate models. The baseline scenario is the one where both climate change and air pollution are considered. The no-air-pollution-increase (NAPI) scenario is the one where only climate change effect is considered (N deposition and CO_2 concentration are fixed at their year 2000 value).

We see a different picture in case of Aladin HU and Aladin CHMI. The difference between the NAPI and the baseline scenario is explained by the CO_2 fertilization effect, not by nitrogen deposition. There is virtually no effect of nitrogen deposition in the baseline scenario as compared to the NAPI scenario. Moreover, without the CO_2 fertilization effect the magnitude of GPP and Reco start to decline around 2050, and in 2100 their absolute value is actually less that at present. It means that air pollution might modulate the carbon fluxes significantly, and there is no clear picture about the significance of N deposition and increasing ambient CO_2 concentration.

Net primary production is intimately related to agricultural production. In order to estimate possible future changes in the crop yield based on the high resolution climate model simulations we can use the NPP data of the BIOME-BGC model as an alternative to crop models like DSSAT Ceres (Jones et al., 2003). Fig. 5.3.2.3. shows the estimated evolution of NPP based on the climate model output and the BIOME-BGC simulations. The figure also shows the NAPI NPP to provide explanation on the changes. Based on Fig. 5.3.2.3. NPP will increase at a constant rate based on RegCM HU, Aladin HU and Aladin CHMI and RegCM CUNI. There are large fluctuations in NPP based on Aladin HU and Aladin CHMI which might be related to droughts. Based on RegCM HU and RegCM CUNI, the NAPI scenario shows that NPP might still increase but at a lower rate. However, based on Aladin HU and Aladin CHMI, NPP starts to decline at around 2050 without the air pollution effect. This is caused by the lack of CO_2 fertilization, as it is pointed out by Fig. 5.3.2.2.

The increase of NPP indicates an overall increase of yield. As we already pointed out, in managed croplands the harvest is removed from the field, consumed by animals or humans, and the carbon content of the yield returns the atmosphere very soon (typically within a year; Ciais et al., 2007). Increasing yield means increasing CO_2 emission caused by consumption. In order to estimate the carbon cycle related feedback of croplands caused by climate change and air pollution we have to take into account the unchanged NEE (biospheric carbon balance from the atmospheric point of view) and the increasing anthropogenic emission (human and animal consumption related emission). As the model overestimates respiration because of the horizontal transport of harvested biomass (see section 2.2), but the magnitude of this overestimation is not known (especially for the future), we can not conclude about the existence or direction of the carbon cycle related feedback mechanism. Based on our model simulations the soil carbon stocks seem to increase (not shown here) but that can be an artifact of the model logic. As it was pointed out in Section 3.2.1., inclusion of management (harvest) causes soil carbon loss in contrast to those simulations that neglect harvest in the grassland related study. If the same is true for croplands, the soil carbon stocks can decrease which means that climate change and air pollution may even cause a positive feedback to climate change. Due to the uncertainties we would like to stress that at present we can not make clear conclusions about the cropland specific feedback. We need improved model logic and a full carbon accounting system in order to estimate the cropland carbon cycle related processes in the present, and in the future.

Until now we only dealt with annual sums of the different carbon cycle components. From the point of view of agricultural production and practices the seasonal evolution of productivity is also very important. If the warming and air pollution can change the annual cycle it may have consequences that should be considered in decision making (e.g. earlier harvest, irrigation planning, etc.).

The carbon exchange of the biosphere is highly variable on hourly, daily and annual time scales because of the prevailing meteorological conditions (sunshine duration, temperature, precipitation, cloudiness, etc.), and climate fluctuations. Therefore it is quite hard to detect long term daily, monthly or seasonal changes based on the simulation data (see e.g. Fig. 5 in Haszpra et al., 2005). In order to provide robust estimates for the future evolution of the carbon cycle components we have calculated 30-years-long mean annual cycles of NEE (i.e. NEE climatology) and other components. Fig. 5.3.2.4. shows the differences between the mean annual courses of NEE during 2021-50, 2071-2100 and 1971-2000 (reference period) based on different climate model results. It is important to keep in mind that the annual NEE does not change in the future (see Fig. 5.3.2.1.), therefore we only seek changes in the course of the annual cycle.

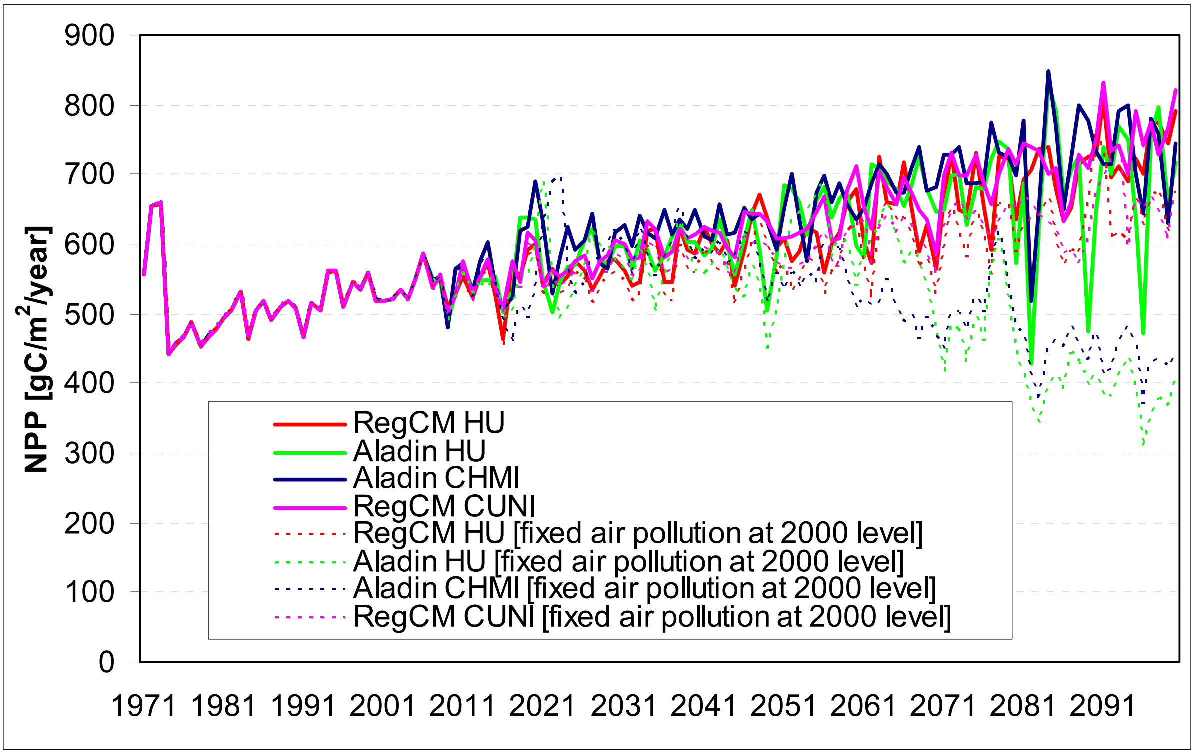

Figure 5.3.2.3. Modelled evolution of net primary production between 1971 and 2100 based on the regional climate model simulations. Solid lines show the estimated NPP with climate change and air pollution impact, while dashed lines show the effect of climate change alone without the air pollution impact (N deposition and CO_2 concentration were held at their respective year 2000 value).

It can be seen on Fig. 5.2.3.4. (left graphs) that NEE becomes more negative (i.e. there is more intensive carbon uptake) in the springtime up to around day 160 (middle of June) both in the 2021-2050 period, and in the 2071-2100 period. This increased carbon uptake might increase the yield of winter crops (e.g. winter wheat). NEE generally decreases after day 160 in the 2021-2050 period, but this decrease is not clear in the 2071-2100 period. In the near future this phenomena can affect the production of summer crops (e.g. maize). The decrease is most probably attributable to summer droughts and increased temperature. There is a secondary increase in NEE around day 260 (middle of September) in both timeslices. This can be caused by early autumn precipitation events and decrease of heat stress on plants. Outside the growing season NEE becomes more positive, which means that there is enhanced respiration from the soil and litter (crop residue). As we could see on the annual plots, the increased respiration balances the increased carbon uptake thus the net effect is approximately zero in NEE. In the meantime we saw that NPP increased, so there might be a benefit from changing climate and increased air pollution for agricultural production.

The right plots on Fig. 5.2.3.4. show the effect of climate change on the annual cycle of NEE without the air pollution effect (nitrogen deposition and CO_2 concentration were held constant after 2000). During the 2021-2050 period the change in the annual cycle is less emphasized compared to the baseline scenario. During the 2071-2100 period RegCM HU and RegCM CUNI predict an increased carbon uptake during the growing season. In contrast, the Aladin HU and Aladin CHMI based simulations show decreasing carbon uptake in the growing season and smaller respiration during the dormant season. Decreasing carbon uptake explains the declining NPP trend in Fig. 5.3.2.3., and the declining GPP and Reco trends after 2050 in Fig. 5.3.2.2. (NAPI scenario). This latter means that air pollution effect is very important considering the modulation of the annual cycle.

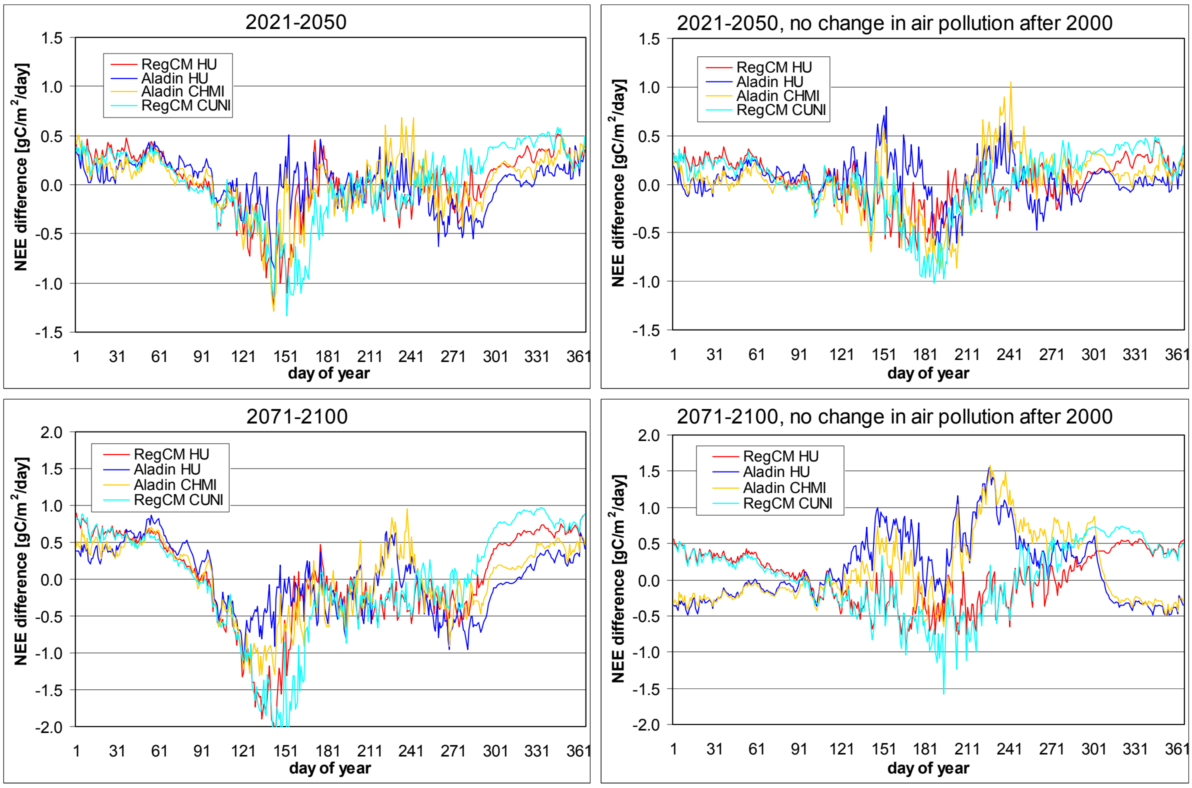

Figure 5.3.2.4. Differences between the mean annual courses of NEE during 2021-50 (upper plots), 2071-2100 (lower plots) and 1971-2000 (reference period) based on different climate model results. Left plots: increasing nitrogen deposition and increasing CO_2 concentration, as a consequence of air pollution, have been taken into account. Right plots: only changes in the meteorological conditions have been taken into account (air pollution effect is not considered, nitrogen deposition and CO_2 concentration were held at the year 2000 level). Negative NEE difference means more carbon uptake than in the 1971-2000 interval.

In order to understand the main driver behind the changes in the annual cycles (left hand side plots versus right hand side plots in Fig. 5.3.2.4) we should separate the effect of climate change, nitrogen deposition and increasing atmospheric CO_2 concentration. As it can be seen in Fig. 5.3.2.5. the NEE cycle is only slightly modulated by the increasing nitrogen deposition during 2021-2050 if CO_2 concentration is fixed at its 2000 value. The effect is higher during 2071-2100 as predicted by the RegCM HU and RegCM CUNI model, but it is zero according to the Aladin HU and Aladin CHMI simulations. The right plots show that CO_2 fertilization effect has a remarkable effect on the annual cycle which can not be neglected. It is especially true during the 2071-2100 period in case of the Aladin HU and Aladin CHMI model. This interesting feature can also be recognized in the annual cycles of GPP and Reco and it is rather consistent among the regional climate models.

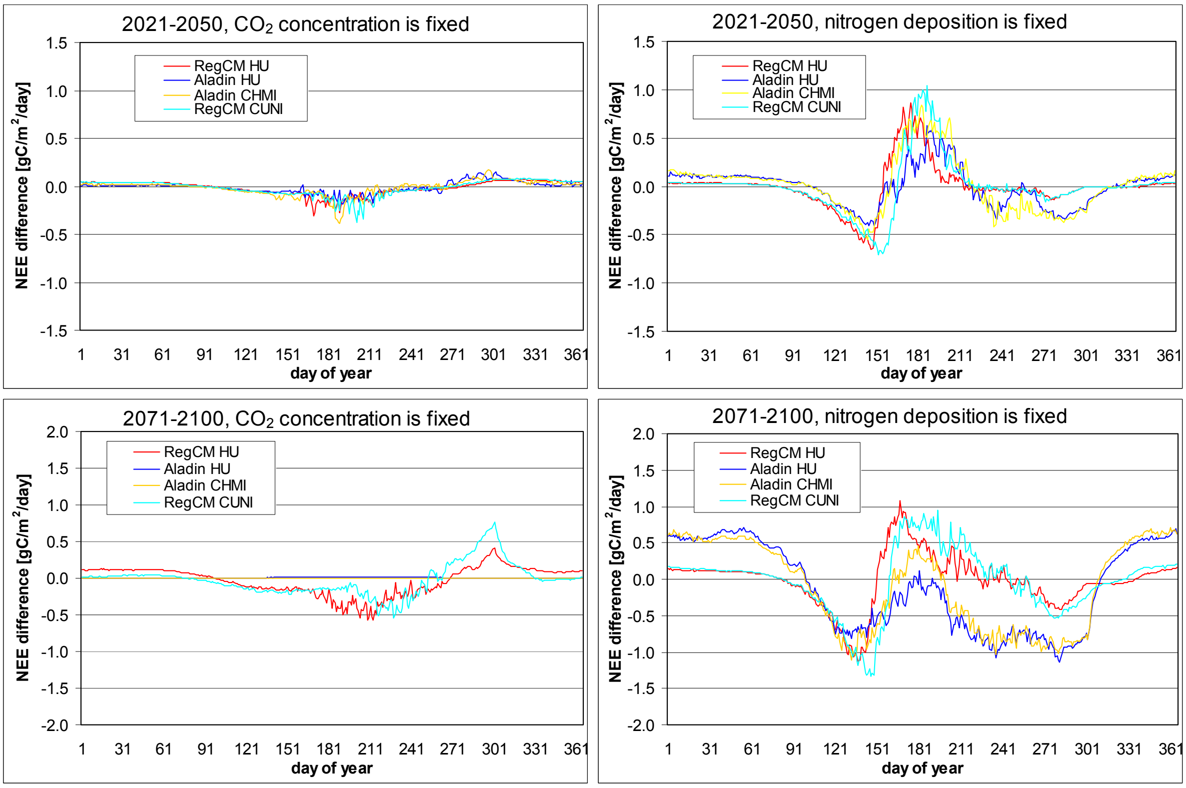

Figure 5.3.2.5. Left: effect of increasing nitrogen deposition on the estimated difference between the mean annual courses of NEE during 2021-2050 and 1971-2000 relative to the no air pollution increase (NAPI) scenario (CO_2 concentration is fixed at the year 2000 level). Right: effect of ambient CO_2 concentration on the estimated difference between the mean annual courses of NEE during 2021-2050 (upper row), 2071-2100 (lower row) and 1971-2000 relative to the no air pollution scenario (Nitrogen deposition is fixed at the 2000 level).

6. Summary

6.1. Conclusions

Based on the carbon cycle related simulations performed with the BIOME-BGC model we could estimate the joint impact of climate change and air pollution on the carbon cycle of two forest ecosystems located in Poland and Slovakia, a managed grassland and a mixed cropland ecosystem located in the Western part of Hungary. The results suggest that climate change and air pollution will act together in a complex manner.

BIOME-BGC based model simulation results for Kampinos forest (Poland) show that there can be large differences between the results obtained with the different kind of ecophysiological parameterizations but the tendencies in evolution of carbon pools, increments and carbon fluxes are almost the same. Carbon content of IPCC pools is increasing continuously during the simulation period (1935-2100). This means that Kampinos forest will likely remain carbon sink in the future. Biomass (stem and root) increments are remaining at the same level (or showing a slight increasing tendency) until 2050, but decreasing tendency is expected afterwards. By this time, climate change may reach a threshold which exceeds the optimum growing conditions for plants.

Net ecosystem exchange (NEE) will remain negative during the simulation period which means the vegetation is likely to remain net carbon sink in the future. We did not find any tendency in NEE thus the amount of sequestered carbon in Kampinos might not be changing in the future. This means that we can not detect any feedback mechanism between climate change and carbon cycle of the Kampinos forest.

Nitrogen deposition has a significantly bigger impact on plants' growth and carbon uptake than elevated atmospheric CO_2-concentration, though its effect differs between the parameterizations. In sandy soils like of Kampinos forest, there is a deficit in reactive nitrogen compounds. If plants get more nitrogen, they may grow faster, taking up more CO_2 from the atmosphere. In case of Kampinos forest this increased uptake can partly compensate the negative impacts of climate change so as the resulting effect is unchanged carbon sequestration capacity of the forest in the future relative to the present day conditions.

To summarize our results based on the Čifáre forest (Slovakia) related simulations, it can be seen that carbon content of IPCC pools is increasing continuously, thus the unmanaged temperate oak forest Čifáre will likely remain a net carbon sink in the future. This finding is corroborated based on the simulated net ecosystem exchange (NEE) data. This means that the forest is likely to remain a net sink of atmospheric carbon dioxide. Soil carbon content is likely to increase which guarantees the forest to be a long-term carbon sink in the future. We found a negative impact of climate change on plant increments: higher mean annual air temperatures strongly decrease stem and root increments. This latter might have a serious impact on timber production, if the results are representative to managed forests.

Climate change and air pollution have a joint impact on the biosphere/atmosphere CO_2-exchange: the magnitude of both gross primary production (GPP) and total ecosystem respiration (Reco) are increasing. The net effect is a slight decrease in the magnitude of NEE (i.e. less carbon is sequestered by the forest in the future as compared to the present day conditions) which may be interpreted as a positive feedback for climate change: with less increment plants can uptake less CO_2 from the atmosphere. The result is increasing atmospheric CO_2 concentration which causes stronger greenhouse effect of the atmosphere, which increases the mean temperatures even further.

We found that the increasing nitrogen deposition has a significant impact on the forest carbon cycle: N stimulates plants' growth so they can take up more CO_2 from the atmosphere. This reduces the positive feedback caused by increasing mean annual temperature mentioned above.

Simulations related to the managed grassland (Hungary) suggest that the increasing CO_2 concentration and increasing nitrogen deposition caused by air pollution increase both the carbon release (Reco; total ecosystem respiration) and the carbon-fixing (GPP; gross primary production). These two effects compensate each other, therefore the net biospheric carbon uptake (NEE) will not change significantly in the examined period (we predict a slight increase in the magnitude of carbon uptake). The effect of increasing CO_2 concentration is proved to be higher than the effect of increasing nitrogen deposition and its effect can be observed throughout the whole year (in contrast to the effect of increasing nitrogen deposition of which the effect is significant only in the growing season).

Grass mowing decreases the soil carbon and therefore the total carbon content of the ecosystem. Examining the separated effects of increasing CO_2 concentration and nitrogen deposition it was found that the increasing CO_2 concentration can compensate a certain part of the carbon loss caused by harvesting. After taking into account the carbon content of the mowed grass it was found that net biome production (NBP) will decrease in the future (which means lower emission of CO_2) but it will remain positive on average. This positive NBP means that the ecosystem will be a carbon source to the atmosphere, but the source intensity is mitigated to some extent by the joint impact of increasing air pollution and climate change. This means a small negative feedback to climate change if we compare the results to the present day situation when the CO_2 release is higher.

The cropland related simulations (Hungary) show that although the net biospheric carbon exchange (NEE) seems to be unchanged in the future, the two large carbon fluxes (GPP and Reco) and also NPP will increase in magnitude as the consequence of climate change and increasing air pollution. Increasing nitrogen deposition and CO_2 concentration will amplify the changes, but there is no simple answer about the importance of the two pollutants. Taking into account both the unchanged NEE (biospheric carbon balance from the atmospheric point of view) and the increasing NPP (which causes increasing anthropogenic CO_2 emission caused by human and animal consumption) we were not able to estimate the direction and magnitude of the carbon cycle related feedback to climate change and air pollution. Human intervention substantially alters the carbon cycle of croplands, and at present we do not have enough information to estimate the fate of cropland carbon cycle in the future. Definitely more research is needed in this topic.

According to our results the annual cycle of agricultural NEE will be modulated in the future, mainly because of the CO_2 fertilization effect. This finding is in accordance with the literature (e.g. Cure and Acock, 1986). The changes might be beneficial as productivity might increase in the first half of the growing season. Some models indicate that without the air pollution effect there can be decrease in productivity and by 2100 crop growth might even decrease.

6.2. Discussion

It is important to note that our forestry and agriculture related simulations use a lot of simplifications, since currently it is not possible to estimate all effects that might interact with the carbon cycle of different terrestrial ecosystems.

For example, in case of croplands it is hard to predict the amount of fertilizers that will be used by the farmers. Fertilization might change a lot in the future, especially because nitrogen deposition will most likely increase, which may be a benefit for the farmers. It means that farmers will be able to decrease the nitrogen amount of the inorganic fertilizers while the harvest might still increase. Our simulation is based on the ‘business-as-usual’ scenario, where we do not assume any change in the amount of applied fertilizers.

Another simplification is the ignorance of changes in the ecophysiological parameters of grasslands, croplands and forests. Plants can get acclimatized to the changing environmental conditions. It means that changes might occur e.g. in the allocation of carbon and nitrogen into the different plant pools. Other important parameters like stomatal conductance and specific leaf area might also be altered in the future as a consequence of climate change and air pollution. Those changes inevitably modulate the carbon cycle. At present we do not have methodology to predict these changes in the ecophysiological parameters.

The current version of the BIOME-BGC model cannot handle air pollution impact other than nitrogen deposition and CO_2 concentration. As an example, ozone can potentially decrease agricultural productivity (Feng and Kobayashi, 2009) but we are not able to account for this effect. Pests, diseases and insect outbreaks might also interact with the forest and agricultural related carbon cycle but those effects are hardly predictable at present. Further studies are needed to include other pollutants and other disturbances in the carbon cycle related simulations. For agriculture uncertainties also arise from possible future changes in the management practices, changes in tillage (application of minimum tillage or no tillage), and a lot of other factors that are consequences of human decisions (date of sowing, harvest, treatment of pests, etc.). Nevertheless, our results indicate that considering air pollution is an essential step in carbon cycle impact simulations.

Acknowledgements

BIOME-BGC version 4.1.1 was provided by the Numerical Terradynamic Simulation Group (NTSG) at the University of Montana. NTSG assumes no responsibility for the proper use of BIOME-BGC by others.

References

Adams, J., 1997. Estimates of preanthropogenic carbon storage in global ecosystem types. Compiled by Jonathan Adams, Environmental Sciences Division, Oak Ridge National Laboratory, TN, USA. http://www.esd.ornl.gov/projects/qen/carbon3.html

Baldocchi, D. D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, Ch., Davis, K., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X., Malhi, Y., Meyers, T., Munger, J. W., Oechel, W., Pilegaard, K., Schmid, H. P., Valentini, R., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001. FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor and energy flux densities. Bull. Am. Meteorol. Soc. 82, 2415-2435.

Baldocchi, D. D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Global Change Biol. 9, 479-492.

Barcza, Z., Haszpra, L., Kondo, H., Saigusa, N., Yamamoto, S., Bartholy, J., 2003. Carbon exchange of grass in Hungary. Tellus 55B, 187-196.

Barcza, Z., Haszpra, L., Somogyi, Z., Hidy, D., Lovas, K., Churkina, G., Horváth, L, 2009. Estimation of the biospheric carbon dioxide balance of Hungary using the BIOME-BGC model. Időjárás - Quarterly Journal of the Hungarian Meteorological Service (in press).

Bartholy, J., Pongrácz, R., Gelybó, Gy., 2007. Regional climate change expected in Hungary for 2071-2100. Applied Ecology and Environmental Research 5, 1-17.

Bürger, G., 1997. On the disaggregation of climatological means and anomalies. Climate Research 8, 183-194.

Christensen, J.H., 2005. Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects. Final Report of the PRUDENCE project. Danish Meteorological Institute, Copenhagen. 269 p.

Churkina, G., Tenhunen, J., Thornton, P., Falge, E.M., Elbers, J.A., Erhard, M., Grunwald, T., Kowalski, A.S., Rannik, U., Sprinz, D., 2003. Analyzing the ecosystem carbon dynamics of four European coniferous forests using a biogeochemistry model. Ecosystems 6, 168-184.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, A., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A. D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J. M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J. F., Sanz, M. J., Schulze, E. D., Vesala, T. and Valentini, R., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature, 437, 529-533.

Ciais, P., Bousquet, P., Freibauer, A., Naegler, T., 2007. Horizontal displacement of carbon associated with agriculture and its impacts on atmospheric CO_2. Global Biogeochem. Cycles, 21, GB2014, doi:10.1029/2006GB002741.

Cienciala, E., Tatarinov, F.A., 2006. Application of BIOME-BGC model to managed forests. 2. Comparison with long-term observations of stand production for major tree species. For. Ecol. Manage. 237, 252-266.

Cox, P.M., Betts, R.A., Jones, C.D., Spall, S.A. and Totterdell, I.J., 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature 408, 184-187.

Cure, J.D. and Acock, B., 1986. Crop responses to carbon dioxide doubling: a literature survey. Agricultural and Forest Meteorology 38, 127-145.

Denman, K.L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P. M., Dickinson, R. E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., da Silva Dias, P. L., Wofsy, S. C. and Zhang, X., 2007. Couplings Between Changes in the Climate System and Biogeochemistry. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. (Eds.: Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Dentener, F. J., 2006. Global Maps of Atmospheric Nitrogen Deposition, 1860, 1993, and 2050. Data set. Available on-line [http://daac.ornl.gov/] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A.

Dentener, F., Drevet, J., Lamarque, J.F., Bey, I., Eickhout, B., Fiore, A.M., Hauglustaine, D., Horowitz, L.W., Krol, M., Kulshrestha, U.C., Lawrence, M., Galy-Lacaux, C., Rast, S., Shindell, D., Stevenson, D., Van Noije, T., Atherton, C., Bell, N., Bergman, D., Butler, T., Cofala, J., Collins, B., Doherty, R., Ellingsen, K., Galloway, J., Gauss, M., Montanaro, V., Müller, J.F., Pitari, G., Rodriguez, J., Sanderson, M., Solmon, F., Strahan, S., Schultz, M., Sudo, K., Szopa, S. and Wild, O., 2006. Nitrogen and sulfur deposition on regional and global scales: A multimodel evaluation. Global Biogeochem. Cycles, 20, GB4003, doi:10.1029/2005GB002672.

Etheridge, D.M., Steele, L.P., Langenfelds, R.L., Francey, R.J., Barnola, J.-M., Morgan, V.I., 1998. Historical CO_2 records from the Law Dome DE08, DE08-2, and DSS ice cores. In: Trends, A. (Ed.), Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN, USA.

Feng, Z., and Kobayashi, K., 2009. Assessing the impacts of current and future concentrations of surface ozone on crop yield with meta-analysis. Atmospheric Environment 43, 1510-1519.

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H.D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K.-G., Schnur, R., Strassmann, K., Weaver, A.J., Yoshikawa, C., and Zeng, N., 2006. Climate-carbon cycle feedback analysis: results from the C4MIP model intercomparison. Journal of Climate 19, 3337-3353.

Giorgi, F., and E. Coppola, 2007. European climate-change oscillation (ECO). Geophys. Res. Lett., 34, L21703, doi:10.1029/2007GL031223.

Haszpra, L., Barcza, Z., Bakwin, P. S., Berger, B. W., Davis, K. J., Weidinger, T., 2001. Measuring system for the long-term monitoring of biosphere/atmosphere exchange of carbon dioxide. J. Geophys. Res. 106D, 3057-3070.

Haszpra, L., Barcza, Z., Davis, K. J., Tarczay, K., 2005. Long-term tall tower carbon dioxide flux monitoring over an area of mixed vegetation. Agric. Forest Meteorol. 132, 58-77. doi:10.1016/j.agrformet.2005.07.002

Haylock, M.R., Hofstra, N., Klein Tank, A.M.G., Klok, E.J., Jones, P.D., New., M., 2008. A European daily high-resolution gridded data set of surface temperature and precipitation for 1950-2006. Journal of Geophysical Research 113, D20119. doi:10.1029/2008JD010201.

Hidy, D., Barcza, Z., Haszpra, L., Churkina, G., Trusilova, K., 2007. Parameter estimation for grassland carbon cycle using nonlinear inversion of Biome-BGC. Cereal Research Communications 35, 453-456. doi: 10.1556/CRC.35.2007.2.72

Hollinger, D. Y. and Richardson, A. D., 2005. Uncertainty in eddy covariance measurements and its application to physiological models. Tree Physiology 25, 873-885.

IPCC, 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry. (Eds. Jim Penman, Michael Gytarsky, Taka Hiraishi, Thelma Krug, Dina Kruger, Riitta Pipatti, Leandro Buendia, Kyoko Miwa, Todd Ngara, Kiyoto Tanabe and Fabian Wagner). Intergovernmental Panel on Climate Change. IPCC/IGES, Hayama, Japan.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Eds.: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., Miller, H. L.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jansen, E., Overpeck, J., Briffa, K. R., Duplessy, J.-C., Joos, F., Masson-Delmotte, V., Olago, D., Otto-Bliesner, B., Peltier, W. R., Rahmstorf, S., Ramesh, R., Raynaud, D., Rind, D., Solomina, O., Villalba, R., and Zhang, D., 2007. Palaeoclimate. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. (Eds.: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. and Miller, H.L.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 433-497.

Janssens, I. A., Freibauer, A., Schlamadinger, B., Ceulemans, R., Ciais, P., Dolman, A. J., Heimann, H., Nabuurs, G.-J., Smith, P., Valentini, R. and Schulze, E.-D., 2005. The carbon budget of terrestrial ecosystems at country-scale - a European case study. Biogeosciences 2, 15-26.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, T.J., 2003. The DSSAT cropping system model. Europ. J. Agronomy 18, 235-265.

Józefaciukowa, W., 1975. The biomass of the root systems of the pine and oak in the Kampinos National Park. Ekol. Pol. 23, 1, 83-92.

Keeling, C.D., Whorf, T.P., 2004. Atmospheric CO_2 concentrations - Mauna Loa Observatory, Hawaii, 1958–2003 (revised June 2004). NDP-001. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee. Available online at http://cdiac.ornl.gov/ftp/maunaloa-co2/.

Kimball, J.S., Running, S.W., Nemani, R., 1997. An improved method for estimating surface humidity from daily minimum temperature. Agricultural and Forest Meteorology 85, 87-98.

Magnani, M., Mencuccini, M., Borghetti, P. Berbigier, F. Berninger, S. Delzon, A. Grelle, P. Hari, P.G. Jarvis, P. Kolari, A.S. Kowalski, H. Lankreijer, B.E. Law, A. Lindroth, D. Loustau, G. Manca, J.B. Moncrieff, M. Rayment, V. Tedeschi, R. Valentini and J. Grace, 2007. The human footprint in the carbon cycle of temperate and boreal forests. Nature 447, 848-850.

Morales, P., Hickler, T., Rowell, D.P., Smith, B., Sykes, M.T., 2007. Changes in European ecosystem productivity and carbon balance driven by Regional Climate Model output. Global Change Biology 13, 108-122. doi: 10.1111/j.1365-2486.2006.01289.x

Nakicenovic, N., Alcamo, J., Davis, G., DeVries, B., Fenhann, J., Gaffinm S., Gregory, K., Gruebler, A., Jung, T.Y., Kram, T., Lebre LaRovere, E., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H.-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., VanRooijen, S., Victor, N., Dadi, Z., 2000. Special Report on Emissions Scenarios: A

Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, 599 pp.

New, M., Lister, D., Hulme, M. and Makin, I., 2002. A high-resolution data set of surface climate over global land areas. Climate Research 21, 1-25.

Pietsch, S.A., Hasenauer, H., Thornton, P.E., 2005. BGC-model parameters for tree species growing in central European forests. For. Ecol. Manage. 211, 264-295.

Running, S. W. and Coughlan, J. C., 1988. A general model of forest ecosystem processes for regional applications I. Hydrological balance, canopy gas exchange and primary production processes. Ecological Modelling 42, 125-154.

Running, S. W. and Gower, S. T., 1991. Forest-BGC, A general model of forest ecosystem processes for regional applications II. Dynamic carbon allocation and nitrogen budgets. Tree Physiology 9, 147-160.

Running, S. W. and Hunt, E. R. J., 1993. Generalization of a forest ecosystem process model for other biomes, Biome-BGC, and an application for global-scale models. In: Scaling physiological processes: leaf to globe (Eds.: Ehleringer, J. R., Field, C. B.). San Diego (CA): Academic Press. pp. 141-158.

Schär, C., Vidale, P. L., Lüthi, D., Frei, C., Häberli, C., Liniger, M. A., Appenzeller, C., 2004. The role of increasing temperature variability in European summer heatwaves. Nature 427, 332-336.

Somogyi, Z. 2008. A hazai erdők üvegház hatású gáz leltára az IPCC módszertana szerint (Greenhouse gas inventory of forests in Hungary using the IPCC methodology). Erdészeti Kutatások 92, 145-162.

Tatarinov, F.A., Cienciala, E., 2006. Application of BIOME-BGC model to managed forests. 1. Sensitivity analysis. For. Ecol. Manage. 237, 267-379.

Thornton, P.E., Running, S.W., 1999. An improved algorithm for estimating incident daily solar radiation from measurements of temperature, humidity, and precipitation. Agric. Forest Meteorol. 93, 211-228.

Thornton, P.E., 2000. User's Guide for BIOME-BGC, Version 4.1.1. Available online at ftp://daac.ornl.gov/data/model_archive/BIOME_BGC/biome_bgc_4.1.1/comp/bgc_users_guide_411.pdf).

Thornton, P.E., Law, B.E., Gholz, H.L., Clark, K.L., Falge, E., Ellsworth, D.S., Goldstein, A.H., Monson, R.K., Hollinger, D., Falk, M., Chen, J., Sparks, J.P., 2002. Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests. Agricultural and Forest Meteorology 113, 185-222.

Vetter, M. Churkina, G., Jung, M., Reichstein, M., Zaehle, S., Bondeau, A., Chen, Y., Ciais, P., Feser, F., Freibauer, A., Geyer, R., Jones, C., Papale, D., Tenhunen, J., Tomelleri, E., Trusilova, K., Viovy, N. and Heimann, M., 2008. Analyzing the causes and spatial pattern of the European 2003 carbon flux anomaly using seven models. Biogeosciences, 5, 561-583, 2008.

Wang, Q. X., Watanabe, M. and Ouyang, Z., 2005. Simulation of water and carbon fluxes using BIOME-BGC model over crops in China, Agric. Forest Meteorol., 131, 209–224, 2005.

Wawrzoniak, J., Małachowska, J., Solon, J., Fałtynowicz, W., Zajączkowski, S., Wyrzykowski, S., Wójcik, J., Adamski, L., Kluziński, L., Sierota, Z., Lech, P., Załęski, A., Kolk, A., 2000. Stan zdrowotny lasów Polski w 1999 roku. Insp. Ochr. Środ., Bibl. Monitor. Środ., Warszawa, 56 pp.

White, M.A., Thornton, P.E., Running, S.W., Nemani, R.R., 2000. Parameterization and sensitivity analysis of the BIOME-BGC terrestrial ecosystem model: net primary production controls. Earth Interactions 4, 1-85.

Zianis, D., Muukkonen, P., Mäkipää, R., Mencuccini, M., 2005. Biomass and stem volume equations for tree species in Europe. Silva Fennica Monographs 4, pp. 63.