Biogeosciences

The response of the terrestrial biosphere to urbanization: land cover conversion, climate, and urban pollution

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Abstract. Although urban areas occupy a relatively small fraction of land, they produce major disturbances of the carbon cycle through land use change, climate modification, and atmospheric pollution. In this study we quantify effects of urban areas on the carbon cycle in Europe. Among urbanization-driven environmental changes, which influence carbon sequestration in the terrestrial biosphere, we account for: (1) proportion of land covered by impervious materials, (2) local urban meteorological conditions, (3) urban high CO_2 concentrations, and (4) elevated atmospheric nitrogen deposition. We use the terrestrial ecosystem model BIOME-BGC to estimate fluxes of carbon exchange between the biosphere and the atmosphere in response to these urban factors.

We analysed four urbanization-driven changes individually, setting up our model in such a way that only one of the four was active at a time. From these model simulations we found that fertilization effects from the elevated CO_2 and the atmospheric nitrogen deposition made the strongest positive contributions to the carbon uptake ($0.023\,\mathrm{Pg\,C\,year^{-1}}$ and $0.039\,\mathrm{Pg\,C\,year^{-1}}$, respectively), whereas, the impervious urban land and local urban meteorological conditions resulted in a reduction of carbon uptake ($-0.005\,\mathrm{Pg\,C\,year^{-1}}$ and $-0.007\,\mathrm{Pg\,C\,year^{-1}}$, respectively). The synergetic effect of the four urbanization-induced changes was an increase of the carbon sequestration in Europe of $0.058\,\mathrm{Pg\,C\,year^{-1}}$.

1 Introduction

Urban population is growing at a much faster rate than the Earth's total population (WRI, 1996) and this leads to the growth of urban areas and often to an increase of urban pollution. Effect of urbanization on vegetation cover depends on the form of urbanization and climatic region. Low density housing development may increase vegetation fraction and potential carbon uptake, e.g. if lawns and gardens replace agricultural fields. In desert and semi-desert regions urbanization also leads to an increase in vegetation cover. For Europe in particular, declining of vegetated land caused by urban growth was documented in the report of Lavalle et al. (2002). As urban areas continue to grow potential carbon sink on land is shrinking because vegetated land is replaced by land covered with impervious materials (buildings, roads, parking lots, etc.). Although urban areas occupy a small land fraction of about 2–3% of the Earth's surface (WRI, 1998), they are sources of about 90% of anthropogenic carbon dioxide (CO_2) globally. In Europe, about 70% of nitrogen dioxide emissions are attributed to traffic (USGS, 1999) and, thus, to urbanized land. At the same time, due to high energy consumption and often lack of evaporation, a warmer and drier microclimate is maintained within urban areas. All consequences of urban development mentioned above have a great potential to influence the carbon cycle and to cause irreversible damage to the surrounding land ecosystems.

Attempts to quantify the role of urban areas on the global carbon budget have focused largely on emissions inventories and carbon sequestration in urban ecosystems. Earlier studies focused on different but single aspects of urbanization and its effects on our environment such as land use modifications (USGS, 1999), global climate change (Parker, 2004; Jones et al., 1990; Wood, 1988; Kukla et al., 1986), climate modifications at regional and local scales (Trusilova et al., 2008; Lamptey et al., 2005), and atmospheric pollution (ESA, 2004; Koerner and Klopatek, 2002; WRI, 1998). It was found that the enrichment of atmospheric CO_2 results in an increased Net Primary Productivity (NPP) of plants (Idso and Kimball, 2001; Hollinger et al., 1999; Dewees and Saxena, 1995). Significant fertilisation effects of atmospheric nitrogen were described in the work of Churkina et al. (2007). However, little research was done on investigating

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the synergetic effects of these two and the urban climate on the land biosphere. One of the major difficulties in quantifying such synergetic effects is that urbanization affects the environment on different scales: from local (land use change) and regional (urban climate) to continental (high concentrations of CO_2 and nitrogen compounds).

In this study we estimate synergetic effects of local-, regional- and continental-scale changes driven by urbanization on the terrestrial biosphere in Europe. We use a biogeochemical terrestrial ecosystem model BIOME-BGC to estimate responses in the net carbon flux to the urbanization-driven changes in land cover, climate, atmospheric CO_2 concentrations, atmospheric deposition of nitrogen that comes from oxides of nitrogen (NO_x) produced during combustion, and the synergetic effect of all these four changes together. We chose to include only nitrogen and CO_2 fertilisation effects in our simulations because those are direct effects which are well represented by a variety of process-based biosphere models.

In this study we omitted including damaging effects of ozone on vegetation growth (Chameides et al., 1994) because ozone has short lifetime of 1–2 days, its concentrations tend to be highest in urban areas and, thus, it affects urban vegetation very locally; mechanisms of these effects are not well understood and are poorly represented in biosphere models. Therefore we most likely slightly overestimate carbon sink in the simulation with all environmental changes included.

2 Materials and methods

2.1 Model

The terrestrial ecosystem model BIOME-BGC (Trusilova and Churkina, 2008; Thornton et al., 2002; Thornton, 1998; Running, 1994; Running and Gower, 1991; Running and Hunt, 1991; Running and Coughlan, 1988) was used to estimate carbon fluxes from vegetation to the atmosphere. The model simulates daily carbon, nitrogen, and water cycles through land ecosystems. This process-based model is driven by daily meteorological data such as maximum and minimum daily temperature, precipitation, vapour pressure deficit, and solar radiation. The land surface is parameterized using a digital elevation map, soil texture data, land cover classification including eight plant functional types, atmospheric CO_2 concentrations and the atmospheric deposition of nitrogen. Each plant functional type is described by ecophysiological parameters.

For this study we defined urban land as in the Corine Land Cover 2000 database (CLC2000, http://terrestrial.eionet.europa.eu/CLC2000): urban land includes areas mainly occupied by dwellings and buildings including their connected areas (associated lands, road network, and parking-lots), rail networks, airport installations, river and sea port installations, industrial livestock rearing facilities, construction

sites, man-made waste dump sites, urban parks, sport and leisure facilities (Bossard et al., 2000). As the CLC2000 urban land mask has resolution of 250 m, this data had to be upscaled to the model resolution.

Effects of urban pollution and climate changes were indirectly included in the simulations as "urban effects". This was done by introducing a relevant change into the input data of the model: (1) urban land fraction as percentage of barren land in the land-use map, (2) bias in temperature and precipitation in the meteorological input dataset for representing urban climate, (3) local elevated urban CO_2 concentrations, and (4) elevated atmospheric nitrogen due to human activities.

2.2 The model simulations

The model domain for this study covers most of Europe, 15° W–45° E 30° N–60° N, with a spatial resolution of 0.25 degrees for the land surface data and meteorological fields. The meteorological dataset was generated with the regional climate model REMO (Jacob and Podzun, 1997) for multi-decadal atmospheric modelling for Europe: the REMO simulations were performed on a rotated spherical grid with a horizontal resolution of 0.5 degrees that corresponds to about 47–55 km in the zonal direction and 55 km in the meridional direction. The full model output was stored hourly (Feser et al., 2001); then, the data was disintegrated to the spatial resolution of 0.25 degrees by Chen et al. (2007).

The REMO model has no explicit urban area definition and no specific land surface scheme for urban land cover. Urban areas are only implicitly included in REMO through the land surface parameters: roughness length (2.5 m), albedo (0.2), zero vegetation fraction, and zero water holding capacity. The land surface parameters for each grid cell were averaged from the data on 1 km spatial resolution. Thus, for large grid cells on 0.5 degrees resolution few grid cells with urban land cover had a minor effect on the climate. These data were aggregated to the daily time step and included minimum and maximum daily temperature, daily precipitation, downward shortwave solar radiation, and air relative humidity.

The USGS global land cover product (Global Land Cover Characterization from U.S. Geological Survey) was used to prepare the map of eight vegetation land cover classes that correspond to the plant functional types resolved by the BIOME-BGC model.

As the BIOME-BGC model does not explicitly resolve urban land cover all urban areas were parameterized as barren surfaces with a small vegetation fraction. We used the same vegetation fraction value, 0.15, as in the work of Trusilova et al. (2008) that was calculated based on the data from Lavalle et al. (2002) for the urban mask on 10 km resolution. This mask of urban land was upscaled to the resolution of 0.25 degrees for this study; for each grid cell of the model domain the urban land fraction was calculated. Only this fraction was assumed urban, not the whole grid cell.
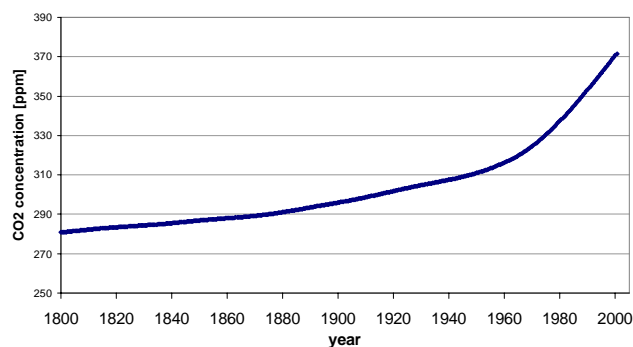
Fig. 1. Background atmospheric CO_2 concentration [ppm] rise used in simulations with the BIOME-BGC model. For each year, one concentration value is uniformly used for all model grid cells assuming that the atmosphere is well-mixed. Data source: CARBOEUROPE-IP database.

2.2.1 Spinup simulation

Carbon and nitrogen state variables of the BIOME-BGC model represent amounts of carbon or nitrogen stored in simulated plant and soil pools. Unless values for the initialization of the model's state variables are available from measurements, model simulations are required for their initialization (spinup run). In the spinup run, the model is run to a steady state to obtain the size of the ecosystem's carbon and nitrogen pools under the assumption of the ecosystem being in equilibrium with the long-term climate. In this simulation the CO_2 concentration was set to a preindustrial level of 283 ppm (Fig. 1), the annual nitrogen atmospheric deposition was set to a constant of $2\,\mathrm{kgN\,ha^{-1}}$, the highest pre-industrial estimate reported by Holland et al. (1999). The meteorological data of 1958–1977 were replicated throughout the spinup simulation. This meteorological data of 20 years were chosen because of three following reasons:

(1) the regional model REMO required the lateral boundary forcing that was first available from 1958 on (ECMWF reanalysis),

(2) these data do not contain any significant temperature trend attributed to the global warming,

(3) the period 1958–1977 is sufficiently long to include the variations of incoming shortwave radiation related to the solar cycle that is of great importance for plant growth.

The spinup run was done for each grid cell of the model domain independently (there is no spatial dependence between model grid cells), until the carbon balance of the ecosystem reached its equilibrium state.

2.2.2 Transient simulation

After the spinup simulation, a transient model simulation was performed for 1800–1957 with repeated meteorological data from 1958–1977, atmospheric nitrogen deposition gradually rising (Galloway et al., 2004), and with the increasing annual

Table 1. . Model setup for simulating different urbanization-driven changes of the terrestrial biosphere. Different urban factors were switched on (Y) and off (N) at the time of model simulations.

Simulation	Description	Disturbances Urban land	Urban climate bias	Urban CO_2 increment	Atm. nitrogen deposition
NOU	Baseline simulation	N	N	N	N
ULAND	Effects of urban land	Y	N	N	N
UMET	Effects of urban warm and dry environment	N	Y	N	N
UCO2	Effects of urban elevated CO_2 concentrations	N	N	Y	N
UAND	Effects of elevated atm. nitrogen deposition	N	N	N	Y
UALL	Synergetic effect of all four factors	Y	Y	Y	Y

mean atmospheric CO_2 supplied by the CARBOEUROPE-IP project (http://www.carboeurope.org/). The atmospheric CO_2 concentration (Fig. 1) represents a smooth change in the well mixed atmosphere and was used as the background value for all following model simulations. The carbon dioxide concentration within the model was updated annually using the same background value for all grid cells. The state variables from the transient simulation ending in 1957 were used as starting point for subsequent simulations from 1958 to 2003 that include different urban effects.

2.2.3 Simulation of urbanization-driven changes

In order to isolate effects of individual urbanization-driven changes on the terrestrial net ecosystem exchange of carbon during the time from 1958 to 2003, six model simulations were performed. Model drivers for each simulation were set up in such a way that they represented none, one, or all urbanization effects (Table 1).

The NOU-simulation was the reference model run, which included no changes due to urbanization. Each of UMET, ULAND, UAND, and UCO2 simulations included one of the urbanization-driven changes such as urban land, urban climate bias, elevated carbon dioxide concentrations, and atmospheric nitrogen deposition, respectively. The UALL simulation represented a synergetic effect of all individual urban-related changes of the terrestrial biosphere.

For the *baseline NOU-simulation* the atmospheric nitrogen deposition was fixed at the level of 1958, the atmospheric CO_2 concentration was set at the level of 294.8 ppm (year 1958) assuming no rise throughout the simulation. The NOU-land-cover map, which includes no urban land, was used. No additional urban change was introduced to the meteorological data fields of the model.
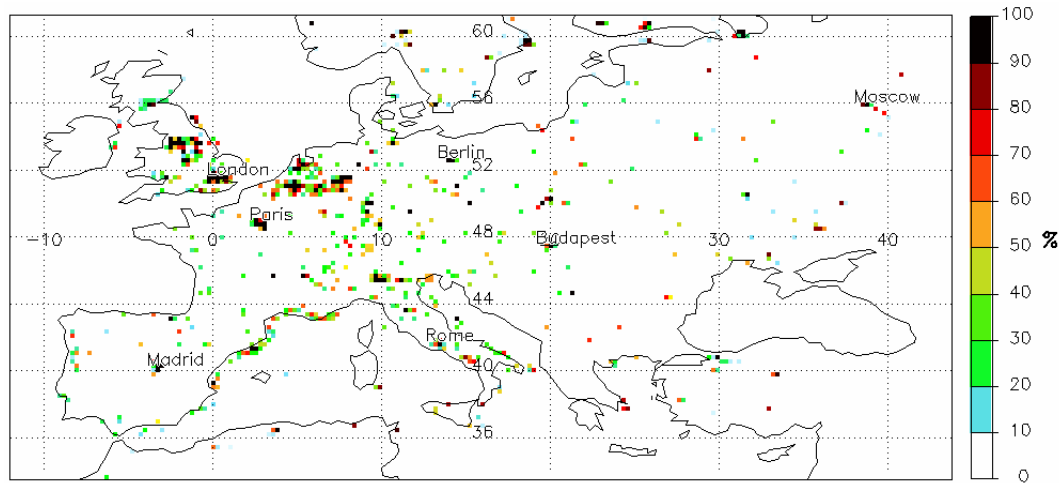
Fig. 2. Fraction of urban land [%] in grid cells of the model domain. Spatial resolution of the grid cell is 0.25×0.25 degrees.

ULAND-simulation. The ecosystem carbon fluxes of the ULAND simulation were calculated with the model setup as in the NOU simulation with the only difference being that a part of these fluxes proportional to the fraction of urban land (Fig. 2) was subtracted. As in this study we assumed that urban areas had just the small vegetation fraction it was expected that urban land acts as a source rather than a sink of carbon; 2.8% of the total land in the model domain was urban.

UMET-simulation. The landscape alteration through urbanization involves the transformation of the radiative and aerodynamic characteristics of the land surface and results in changes of the water cycle and planetary boundary layer. Such altered environments are likely to experience extreme temperatures (Gonzalez et al., 2005; Jin et al., 2005; Ca et al., 1998; Jauregui, 1991; Huang et al., 1987; Bernatzky, 1982) and urban heat island phenomena (Atkinson, 2003; Borghi et al., 2000; Brunetti et al., 2000) as well as changes of precipitation (Dixon and Mote, 2003; Rosenfeld, 2000; Huff and Changnon, 1973) and reduced air moisture and evaporation in cities (Mayer et al., 2003; Grimmond and Oke, 1999). Quantitative estimates of the effects of urban land on the local climate were taken from the study of Trusilova et al. (2008), who analysed differences in near-surface temperature and precipitation between an undisturbed (without urban land) and a present day atmospheric circulation in Europe. It was found that the conversion of rural to urban land results in statistically significant reduction of the diurnal temperature range by 1.26±0.71°C in summer and by 0.73±0.54°C in wintertime as well as changes of precipitation (an increase in winter by +0.09±0.16 mm day^{-1} and a reduction in summer by 0.05±0.22 mm day^{-1}). These estimates were calculated assuming that all urban areas have homogeneous structure: all buildings are of the same height and all street canyons of the same shape. The urban surface scheme used by Trusilova et al. (2008) was generalized in

order to represent large horizontal scales (10–100 km) and to be able to capture radiative budgets, momentum, turbulent heat and ground fluxes from heterogeneous urban surfaces. Such generalisation allowed model applicability for multiple urban areas in the large model domain.

The extracted maps of urbanization-induced changes for temperature and precipitation were superimposed on the input meteorological fields for the BIOME-BGC model.

UCO2-simulation. Near the surface, large urban clusters often are "hot spots" of intensive CO_2 release from diffuse sources of anthropogenic origin (Koerner and Klopatek, 2002; Idso et al., 2001): transport network, industrial emissions etc. Scarce measurements of urban CO_2 are available that were taken in various locations and times with different instrumental setups. In the study of Rome, Italy (Gratani and Varone, 2005) carried out through 1995, 1998, and 2001–2004, CO_2 concentrations measured on the street level of 2 m above ground in the city were by 15%–23% higher than in the baseline CO_2 concentration (NOU-simulation). In the study of Krakow, Poland (Zimnoch et al., 2004) in 1994, measurements of 24% higher urban CO_2 were registered at 20 m above ground level, in the area without direct low-emission sources and without car traffic nearby. The highest CO_2 concentrations were registered in Paris, France (Widory and Javoy, 2003) at few metres above ground level in short-term campaigns in 1997–1998 that was higher by 7%–220% than the background value. The measurement campaign that has been conducted in the Metropolitan area of Copenhagen in 2000–2002 registered up to 86% higher CO_2 concentrations at the level of 10 m above ground in urban core relative to suburban areas. All mentioned above studies relate the highest CO_2 values mainly to the vehicle exhausts. Following this assumption we have constructed an approximation of the urban-to-rural CO_2 concentration increment (ΔCO_2) using the urban land mask. We used the updated urban mask (Trusilova et al., 2008) that includes information about the
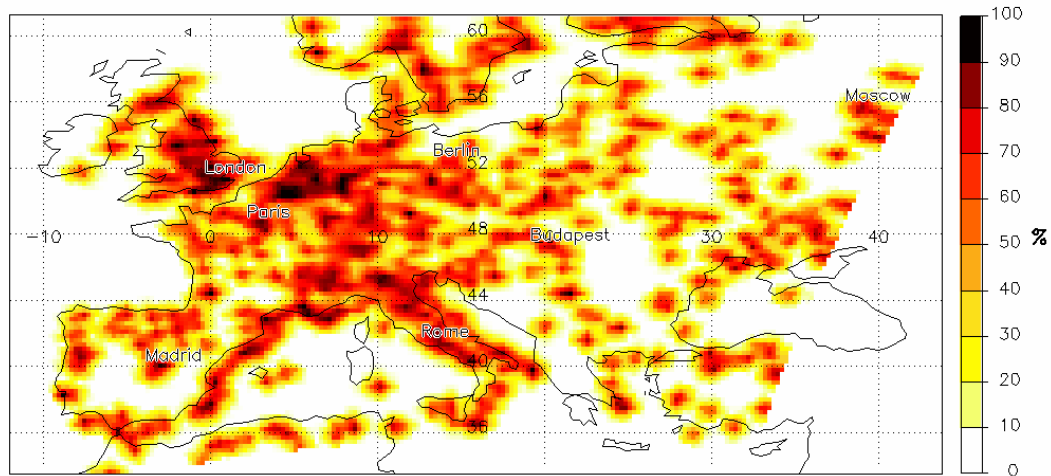
Fig. 3. The spatial distribution of ΔCO_2 – increment of urban carbon dioxide concentration in relation to the background rural value [%] in carbon dioxide concentrations (ΔCO_2) between urban and rural land relative to the background CO_2 concentration.

population density and light emissions data as a proxy for constructing ΔCO_2. The main principle for this construction is: the larger the proportion of urban land in a gridcell the higher is the CO_2 emissions and as follows the CO_2 concentrations. Applying this principle requires the assumption that the CO_2 exhaust intensity is the same across all urban pixels in Europe. The estimation of ΔCO_2 was done for the street level (several metres above ground) where most of vegetation will be affected by it. For such rough estimate at this height no atmospheric transport model was needed to resolve vertical and horizontal gradients in ΔCO_2 distribution. We assumed the homogeneous vertical distribution of ΔCO_2 within the first several metres above ground (<10); the horizontal gradients were estimated using the urban land fraction data. Taking into account the reported magnitude of the CO_2 concentrations we constructed a map of urban–to–rural ΔCO_2 that was calculated from the fraction of urban land (Fig. 3):

$$\Delta CO_2[i, j] = \Delta co_2 \frac{1}{(2r+1)^2} \int_{i-r}^{i+r} \int_{j-r}^{j+r} S_{\text{urb}}[i, j] dx dy,$$

where i, j – grid cell coordinates, r – distance of the smoothing of influence, $r=2$; it insures that neighbour pixels do not get extremely different values, $S_{\text{urb}}[i, j]$ – urban area within the r-distance from the centre in the pixel $[i, j]$; devided by the $(2r+1)^2$ gives the fraction of urban land in the area defined by $[i-r, i+r]$ and $[j-r, j+r]$,

Δco_2 – proportion of the CO_2 increment per one urban grid cell [%] as approximated from the available measurements in the following way: from the assumed linear relationship between the size of the city and the magnitude of the CO_2 increment (for a city 10×10 pixels large it was 100%, for a city 10 pixels large it was 32%).

The ΔCO_2 was then used as an additional model input and included into the calculation of total input CO_2 concentration for each grid cell as:

Input_$CO_2[i, j]$=Background_$CO_2 \times (1 + \Delta CO_2[i, j])$,

where Input_CO_2 is the CO_2 concentration value for a grid cell $[i, j]$, and Background_CO_2 is the input annual background carbon dioxide concentration (the same value for all grid cells throughout the simulation).

UAND-simulation. In contrast to the NOU-simulation, the data on dry atmospheric nitrogen deposition for the UAND-simulation corresponds to the year 2003. As the model was run from 1958 to 2003, the nitrogen deposition was gradually interpolated from the value at the beginning of the simulation (Fig. 4a) to the value in the end of the simulation (Fig. 4b) for each model pixel. This yielded an additional input of 8.86 Tg of nitrogen over 46 years in the model domain.

The *UALL-simulation* was performed with all four urbanization-driven changes included: the elevated CO_2 concentrations, the rising nitrogen deposition, fraction of urban land, and the urbanization-induced changes in local climate. As the BIOME-BGC model simulates interactions of carbon, nitrogen, and water cycles, including all four urban factors represented the synergetic effect of urban pollution, land use, and local climate on the carbon sequestration of European land ecosystems.

3   Analysis of model output

In order to quantify responses of the land ecosystems we analysed the following carbon fluxes calculated by the BIOME-BGC model: Net Ecosystem Exchange (NEE), Gross Primary Production (GPP), and Total Ecosystem Respiration (TER). The latter was calculated as a sum of
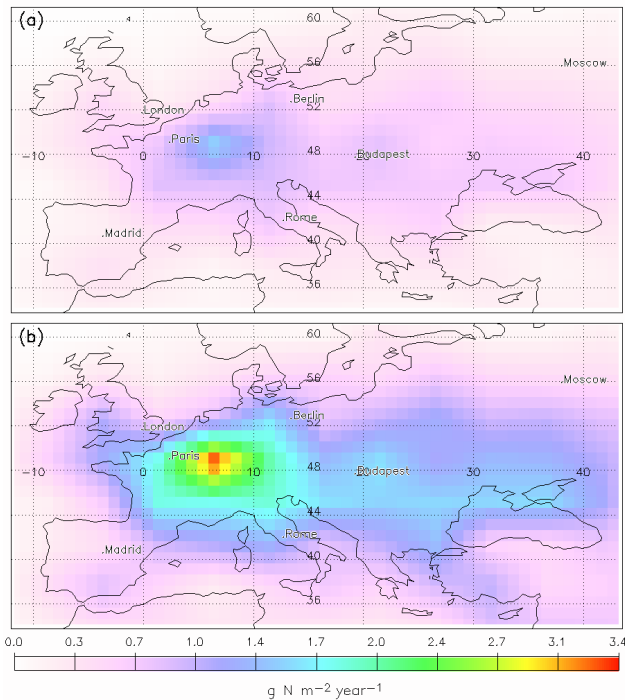
Fig. 4. Dry nitrogen atmospheric deposition [g N m^{-2} year^{-1}] in 1958 **(a)** and 2003 **(b)**. Data source Galloway et al. (2004).

heterotrophic respiration, plant growth respiration, and maintenance respiration.

We calculated differences in modelled carbon fluxes from each of the simulations ULAND-, UMET-, UCO2-, and UAND- and the baseline NOU-simulation. We used these differences as quantitative estimates of the sensitivity of the carbon fluxes to the respective urbanization-driven change. The flux difference between the UALL and NOU simulations was interpreted as the response of the biosphere to all counteracting urban changes together.

We calculated the total difference in the GPP, TER, and NEE over the model domain as the sum over differences in individual pixels:

$$C\,(\text{FLX, sim}) = \frac{1}{N} \int\limits_{dt} \int\limits_{dS} (\text{flx}\,(\text{FLX, sim}) - \text{flx}\,(\text{FLX, NOU}))\, dS\, dt,$$

C(FLX,sim) – yearly average amount of carbon attributed to the flux FLX in the simulation sim,
FLX – GPP, TER or NEE flux in the simulation sim,
sim=ULAND | UMET | UAND | UCO2 | UALL simulation,
N – total number of simulated years (N=46),
flx(FLX, sim) – flux FLX of one the grid cell in the simulation sim, [Pg C m^{-2} year^{-1}],
S – area of model domain, [m^2],
t – time, [year].

4 Results and discussion

Model simulations were performed according to the six setups described above. Modelled GPP, NEE, and TER fluxes from simulations ULAND, UMET, UCO2, UAND, and UALL were analysed in relation to the baseline simulation NOU. The differences between each simulation that includes urban factor(s) and the baseline were interpreted as a quantitative measure of the effect of the respective urbanization-induced change on biosphere.

4.1 Land cover

The conversion of vegetated land to urban caused a reduction of GPP (Fig. 5a1), TER (not shown) and NEE (Fig. 5a2) over perturbed land. The average reduction of the NEE flux over simulated period was -0.005 Pg C year^{-1} in Europe (model domain). This reduction accounted for 0.3% of the yearly average NEE from the relevant area. In this estimate all urban areas have the same vegetation fraction. In reality cities have a blend of land cover types such as trees, grasses, barren, and impervious surfaces in different proportions. To account for the heterogeneity of urban vegetation and its role in the carbon cycle we would have to use very precise satellite-derived maps of urban land cover on fine spatial resolutions of 1–10 m. For example, an estimation of total reduction of net primary production (NPP) in the southeastern US was made by Milesi et al. (2003). Using a remote sensing based methodology, the authors found that an increase in urban development of 1.9% over 1990–2000 resulted in a reduction of NPP by 0.4% over the region. However, the heterogeneity of urban land covers also involves a wider set of model setups in order to represent the full variety of urban ecosystems in our modelling study and it would generate large uncertainties in carbon flux estimates. Thus we focused on a general estimate of the urban effects on the European carbon cycle and, thus, used a rather simplified representation of urban land cover.

4.2 Climate

Responses of GPP and TER fluxes to the urbanization-induced changes in the climate were spatially heterogeneous. In most areas of reduced precipitation GPP and TER flux (growth respiration and heterotrophic respiration components) were reduced. However, the photosynthetic productivity was higher in areas with enhanced precipitation and increased temperature and resulted in local peaks of GPP (Fig. 5b1). The range for GPP changes was -0.22 ± 0.41 kg C m^{-2} year^{-1} and for TER -0.20 ± 0.40 kg C m^{-2} year^{-1}. Since the areas of GPP reduction were larger in extent, they dominated the overall average change in carbon balance -0.007 Pg C year^{-1} over Europe. This could partly be explained by the high sensitivity of the BIOME-BGC model to the soil water availability; the
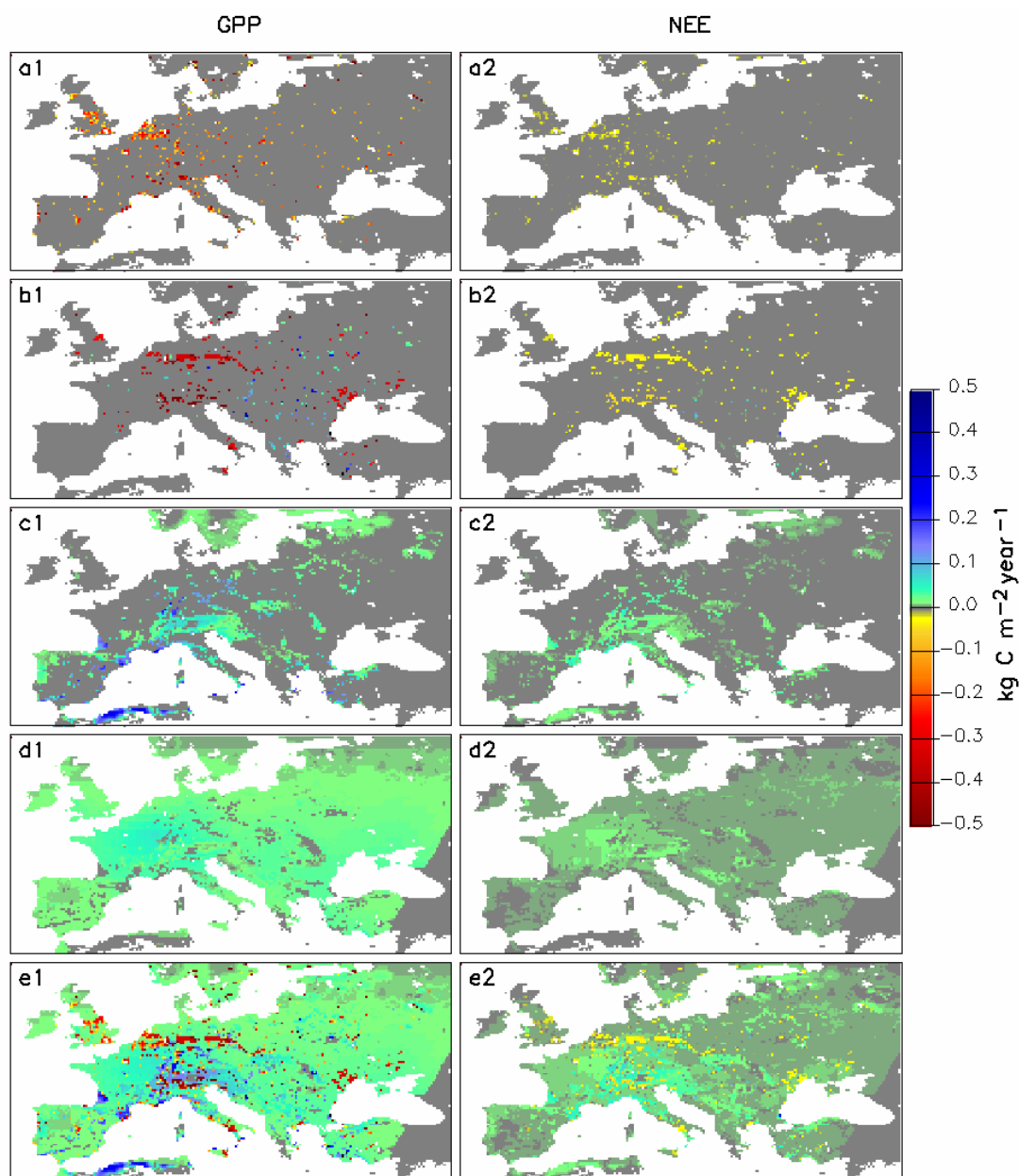
Fig. 5. Response of GPP (a1, b1, c1, d1, e1) and NEE (a2, b2, c2, d2, e2) fluxes to different urbanization-driven changes: urban land (a1, a2), urban climate (b1, b2), urban CO_2 (c1, c2), elevated nitrogen deposition (d1, d2), and all mentioned changes together (e1, e2).

reduced amount of precipitation leads to drying of soils and to the reduction in photosynthetic productivity of plants. The overall effect of climatic changes on carbon balance of Europe was negative and provided enhanced release of carbon from land ecosystems.

4.3 Urban CO_2

An increase in carbon uptake of $(+0.01\pm0.01)\,\mathrm{kg\,C\,m^{-2}\,year^{-1}}$ over large areas, with the highest values up to $0.10\,\mathrm{kg\,C\,m^{-2}\,year^{-1}}$, were found

in Central Europe where densely urbanized areas are located (Fig. 5c1 and 5c2). Effects of CO_2 concentration on plants productivity were previously addressed in several studies. For example, Griffin et al. (2001) found that elevated CO_2 produces significant changes in major cellular organelles of plants and lead to enhanced plant productivity. Taub et al. (2000) found that plants respond to the higher CO_2 by increased thermotolerance of high-temperature stress; and that effect may have a substantial impact (increase) on productivity. Our simulations showed an average increment
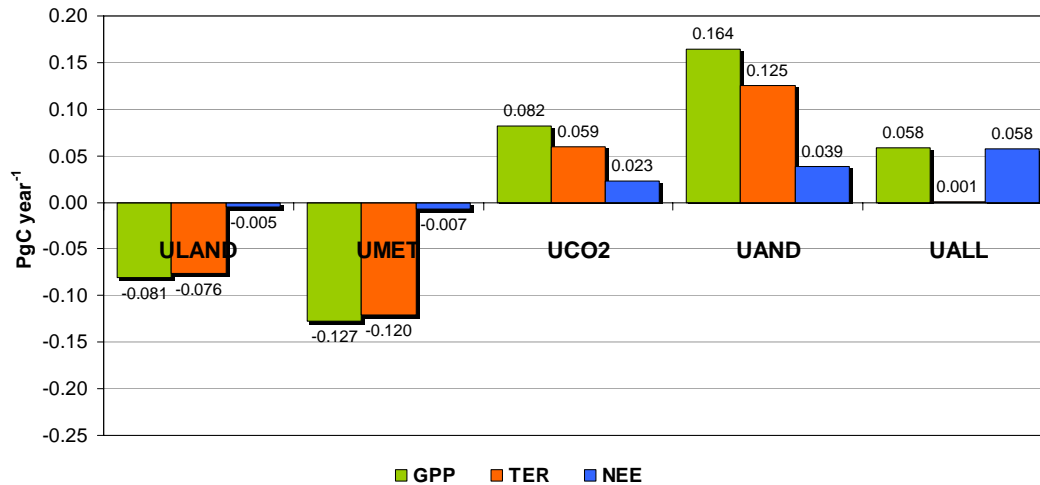
Fig. 6. Changes of carbon amount [Pg C year^{-1}] exchanged between the biosphere and the atmosphere in response to different urban disturbances: urban land (ULAND), urban meteorological bias (UMET), urban CO_2 concentrations (UCO2), anthropogenic nitrogen deposition (UAND), and composition of all four disturbances (UALL). Data are 46-year averages of BIOME-BGC model output over 1958–2003.

of carbon sink by 0.023 Pg C year^{-1} that was dominated by the increase in GPP (Fig. 6). This estimate reflects pure CO_2 fertilization effect on ecosystems in urban and suburban ecosystems.

4.4 Effects of elevated nitrogen deposition

The sensitivity of the GPP flux to the additional atmospheric nitrogen deposition was the highest among all analysed urban changes (+0.164 Pg C year^{-1}). The additional nitrogen to the soils enhanced the microbial activity and lead to the higher heterotrophic respiration component of TER (+0.125 Pg C year^{-1}). The total net carbon flux (NEE) increased over the whole modelled domain by 0.039 Pg C year^{-1}. This result is based on the model assumption that temperate and boreal vegetation is nitrogen limited (Vitousek et al., 2002). An increasing deposition of nitrogen from the atmosphere serves as a fertiliser for European ecosystems. Of all individual urbanization-driven changes studied here, nitrogen deposition has the strongest impacts on the total carbon balance. The role of atmospheric nitrogen deposition on the European carbon balance as a fertiliser is however debatable because of uncertainties of its effects on the agricultural land, which occupies a considerable proportion of Europe. In 1997 arable land together with permanent cropland and pasture covered 44% of EU15 (EUROSTAT, http://ec.europa.eu/agriculture/envir/report/en/terr_en/report.htm). Agricultural land receives high loads of nitrogen directly as chemical fertilizer and therefore insensitive to the increasing deposition of nitrogen from the atmosphere. In this study, we only looked at the effects of atmospheric nitrogen deposition assuming no additional nitrogen-fertilisers are applied on agricultural land. On the other hand, the fraction of agricultural land was declining, while fraction of

forests was increasing in the last 50 years. The European forests are currently young and are in the re-growth stage. The total forest area of 30 European countries has increased by 6% between 1950 and 1990 (Nabuurs et al., 2003). The productivity of regrowing forests is especially sensitive to the increasing atmospheric nitrogen deposition (Churkina et al., 2007).

4.5 Synergetic effects

When all four urbanization-induced changes were applied at once, the biosphere responded with a 0.058 Pg C year^{-1} increase of carbon sink. This increase in NEE resulted from an increase in GPP (+0.058 Pg C year^{-1}) and the slight change in TER (+0.001 Pg C year^{-1}). As the vegetation was replaced by barren land the amount of the potential carbon source through growth respiration was reduced but compensated by the growth of urban fractional vegetation. In the whole model domain, the reduction of carbon sink due to urban land use and climate was compensated by an increase of carbon sink due to fertilisation by simultaneously increasing atmospheric CO_2 and nitrogen deposition.

The synergetic effect of the urbanization-driven changes considered here led to a stronger increase of carbon sink than any of them individually (Fig. 6), because atmospheric CO_2 and soil nitrogen availability co-limit productivity of land ecosystems. This finding is confirmed by field studies where nitrogen availability was shown to be a constraint to CO_2-induced stimulation of plant growth (Reich et al., 2006; Oren et al., 2001). Our results were also in accordance with results from several modelling studies (Churkina et al., 2007; Lloyd, 1999) where numerical models were employed to simulate response of biosphere carbon cycle on the continental level. Low availability of nitrogen in the soils suppresses

the positive physiological response of plant growth to elevated CO_2. Anthropogenic increase in nitrogen deposition enhances availability of nitrogen in soil and thus the response of plants to increasing atmospheric CO_2. Increase in atmospheric nitrogen deposition has been shown to drive the sequestration of carbon by European forests (Magnani et al., 2007).

Relationships between the carbon sequestration rates, nitrogen input, and climate variables are nonlinear and due to this nonlinearity, the total effect on vegetation of all urbanization-related changes together was not equal to the sum of individual effects from individual changes.

5 Summary and outlook

In this study we analysed dynamics of carbon sink in Europe driven by urbanization-induced changes of land use, climate, concentrations of carbon dioxide and nitrogen deposition from the atmosphere. We used the BIOME-BGC terrestrial ecosystem model to calculate responses of the biosphere to the urban changes applied individually and all together. We did not include agricultural management such as field-fertilisation with nitrogen compounds in our simulations.

The land use and urban climate changes affected rather small land areas while the urban CO_2 and nitrogen pollution spread over larger areas. When all urban changes were applied at once, the synergetic effects were dominated by the fertilisation effects from the CO_2 and nitrogen pollution and led to a net increase of carbon sink in Europe.

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