THE RESPONSE OF THE TERRESTRIAL BIOSPHERE TO URBANIZATION: LAND COVER CONVERSION, CLIMATE, AND URBAN POLLUTION

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Abstract

In this study we quantify effects of urban areas on the carbon cycle in Europe accounting for: (1) proportion of impervious land, (2) local urban climate, (3) urban CO_2 concentrations, and (4) elevated atmospheric nitrogen deposition. We use a terrestrial ecosystem model to estimate biosphere-to-atmosphere carbon fluxes in response to these urban factors. It was found that fertilization effects from CO_2 and the atmospheric nitrogen deposition made the strongest positive contributions to the carbon uptake (0.023 Pg C year^{-1} and 0.039 Pg C year^{-1}, respectively), whereas, the impervious urban land and local urban climate resulted in a reduction of carbon uptake (−0.005 Pg C year^{-1} and −0.007 Pg C year^{-1}, respectively). The synergetic effect of the four factors was 0.058 Pg C year^{-1} increase of the carbon sequestration in Europe.

Key words: land cover modifications, urban pollution, carbon cycle modelling

1. INTRODUCTION

Urban population is growing at a much faster rate than the Earth's total population 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. 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, 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 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.

In this study 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. We omitted including damaging effects of ozone on vegetation growth and, 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) was used to estimate carbon fluxes from vegetation to the atmosphere. The model simulates daily carbon, nitrogen, and water cycles through land ecosystems. It is driven by daily meteorological data (temperature, precipitation, vapour pressure deficit, solar radiation). The land surface is parameterized using a digital elevation map, soil texture data, land cover classification (8 plant functional types), atmospheric CO_2 concentrations and the atmospheric deposition of nitrogen. Each plant functional type is described by a set of ecophysiological parameters.

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 3) elevated atmospheric nitrogen due to human activities.

2.2. Model Simulations

The model domain (15°W-45°E 30°N-60°N) covers Europe 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). The USGS global land cover product 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.

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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. Only this fraction was assumed urban, not the whole grid cell.

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**).

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	Urban CO_2	Atm. N dep.
NOU	Baseline simulation	N	N	N	N
ULAND	Effects of urban land	Y	N	N	N
UMET	Effects of urban climate	N	Y	N	N
UCO2	Effects of urban elevated CO_2 conc.	N	N	Y	N
UAND	Effects of elevated atm. N deposition	N	N	N	Y
UALL	Synergetic effect of all four factors	Y	Y	Y	Y

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 CO_2 concentrations, and atmospheric N 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). The land cover map for this simulation included no urban land.

For the UMET-simulation extracted maps of urbanization-induced changes for temperature and precipitation (Trusilova et al., 2008) were superimposed on the input meteorological fields for the BIOME-BGC model.

For the UCO2-simulation the estimation of urban CO_2 was done for the street level where most of vegetation will be affected by it. The urban CO_2 was added to the background CO_2 concentrations as input to the terrestrial ecosystem model.

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 to the value in the end of the simulation for each model pixel.

The UALL-simulation included all four urbanization-driven changes: the elevated CO_2 concentrations, the rising nitrogen deposition, the fraction of urban land, and the urbanization-induced changes in local climate.

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=GPP−NEE). We calculated differences in yearly carbon fluxes of Europe from each of the simulations ULAND-, UMET-, UCO2-, and UAND- and the baseline NOU-simulation and 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.

3. RESULTS AND DISCUSSION

The differences between each simulation that includes urban factors (ULAND, UMET, UCO2, UAND, and UALL) and the baseline NOU were interpreted as a quantitative measure of the effect of the respective urbanization-induced change on biosphere.

3.1. Sensitivity of carbon sequestration to individual urban factors

The conversion of vegetated land to urban caused a reduction of GPP (**Figure 1**a1), TER (not shown) and NEE (**Figure 1**a2) over Europe. The average reduction of the NEE flux over simulated period was −0.005 Pg C year^{-1} over the 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.

Responses of GPP and TER fluxes to the urbanization-induced changes in the climate were spatially heterogeneous. In most areas of reduced precipitation GPP (**Figure 1**b1) and TER (**Figure 1**b2) were reduced. 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}. The GPP reduction dominated the overall average change in carbon balance of −0.007 kg C year^{-1} over Europe.

In response to the urban CO_2 an increase in carbon uptake of (+0.01±0.01) kg C m^{-2} year^{-1} over large areas, with the highest values up to 0.10 kg C m^{-2} year^{-1}, were found in Central Europe where densely urbanized areas are located (**Figure 1**c1,c2). The simulations showed an average increment of carbon sink by 0.023 kg C year^{-1} that was dominated by the increase in GPP (**Figure 2**). This estimate reflects the pure CO_2 fertilization effect on ecosystems in urban and suburban ecosystems.

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 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.

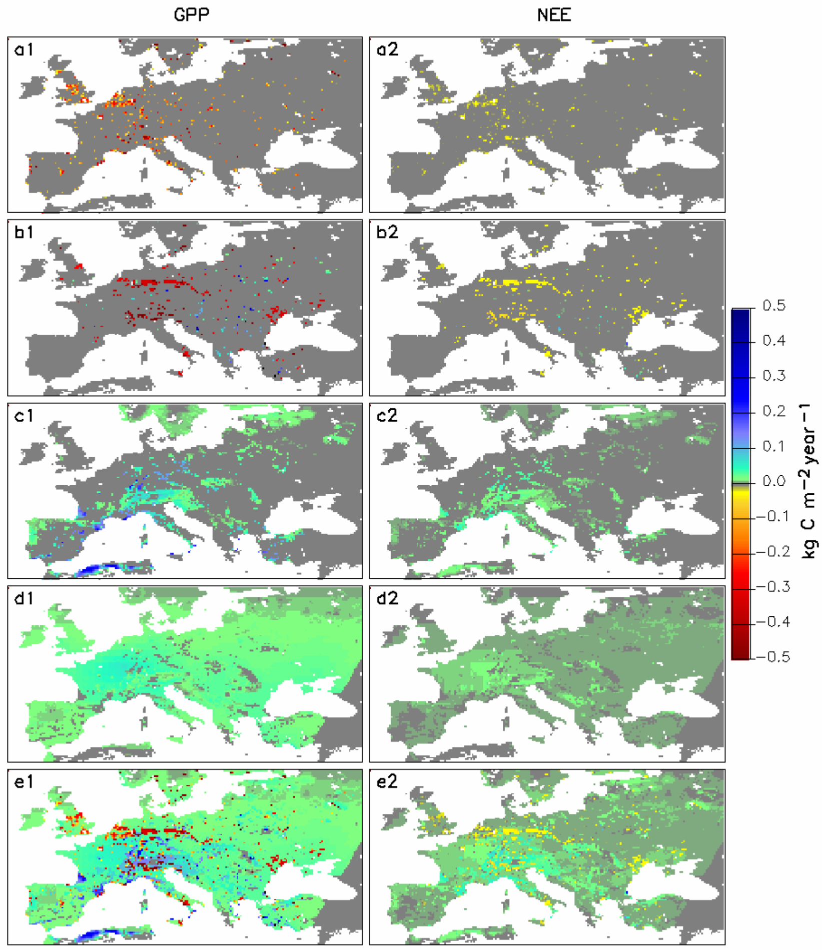

Figure 1. Response of GPP (a1,b1,c1,d1,e1) and NEE (a2,b2,c2,d2,e2) fluxes to different urbanization-driven changes: urban land (a1,a2), urban climate (b1,b2), urban CO_2 (c1,c2), elevated nitrogen deposition (d1,d2), and all mentioned changes together (e1,e2).

3.2. Synergetic effects of urban factors of the carbon balance

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 (**Figure 2**), 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).

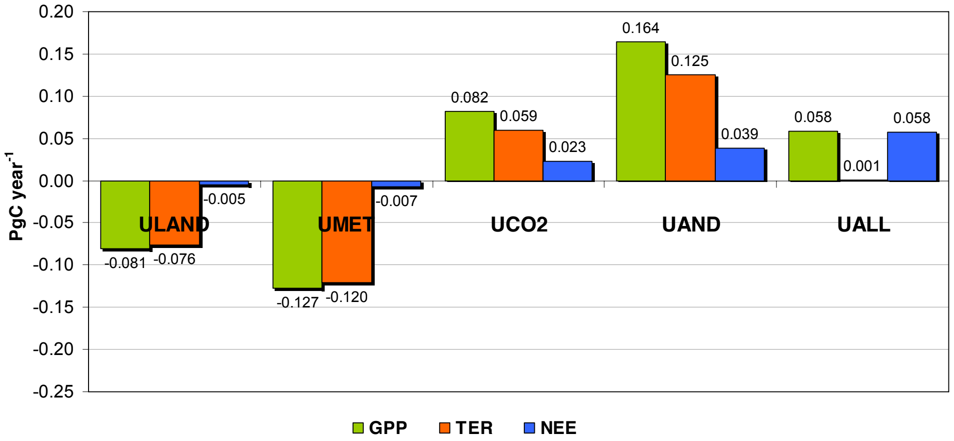

Figure 2. Changes of carbon amount [Pg C year^{-1}] exchanged between the biosphere and the atmosphere in response to different urban disturbances: urban land (ULAND), urban meteorological bias (UMET), urban CO_2 concentrations (UCO2), anthropogenic nitrogen deposition (UAND), and composition of all four disturbances (UALL). Data are 46-year averages of BIOME-BGC model output over 1958-2003.

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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