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Estimation of the biospheric carbon dioxide balance of Hungary using the BIOME-BGC model

Zoltán Barcza[1*], **László Haszpra**[2], **Zoltán Somogyi**[3], **Dóra Hidy**[4], **Katalin Lovas**[5], **Galina Churkina**[6], and **László Horváth**[2]

[1]*Department of Meteorology, Eötvös Loránd University,*
P.O. Box 32, H-1518 Budapest, Hungary; E-mail: bzoli@elte.hu
[2]*Hungarian Meteorological Service,*
P.O. Box 39, H-1675 Budapest, Hungary; E-mails: haszpra.l@met.hu, horvath.l@met.hu
[3]*Forest Research Institute,*
Frankel L. u. 42-44, H-1027 Budapest, Hungary; E-mail: somogyiz@erti.hu
[4]*Institute of Botany and Ecophysiology, Szent István University,*
Páter K. u. 1, H-2103 Gödöllő, Hungary; E-mail: dori.hidy@gmail.com
[5]*Hungarian Meteorological Service,*
P.O. Box 38, H-1525 Budapest, Hungary; E-mail: lovas.k@met.hu
[6]*Max Planck Institute for Biogeochemistry,*
Hans-Knöll-Str. 10, D-07745 Jena, Germany; E-mail: churkina@bgc-jena.mpg.de

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Abstract—Here we estimate the biospheric carbon dioxide balance of Hungary using the adapted BIOME-BGC process oriented ecological system model. The model was calibrated using the Hungarian measurements of biosphere-atmosphere carbon dioxide exchange. After calibration, the model was run for the four major land cover types such as croplands, grasslands, deciduous and coniferous forests for the period of 2002–2007. Our calculations suggest that all Hungarian ecological systems together formed a net carbon dioxide source during the time period studied. Since agricultural fields cover more than 50% of the total area of Hungary, the net carbon dioxide flux is dominated by the carbon balance of croplands. The average net release of CO_2 is 8.7 Mt per year with significant interannual variation: the highest net emission was 21.6 Mt CO_2 in 2003, while the lowest was 1.2 Mt CO_2 in 2006. Due to the model limitations, simulated CO_2 release from croplands is most likely overestimated, thus, the present results provide an upper limit for the potential range of the carbon balance of Hungary. The model results highlight the strong dependence of the biospheric carbon dioxide balance on the weather conditions. The results are compared with the carbon budget estimations previously published for Hungary as well as with those reported to the United Nations Framework Convention on Climate Change.

Key-words: biospheric carbon balance, net ecosystem exchange, ecosystem model, upscaling, eddy covariance measurements, plant functional types, BIOME-BGC model, model calibration

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[*] Corresponding author

1. Introduction

Atmospheric carbon compounds, especially carbon dioxide and methane, play a crucial role in the formation of Earth's climate through the greenhouse effect (*Jansen et al.*, 2007). Their atmospheric amount partly depends on the activity of the biosphere, which is partly climate controlled, but also considerably affected by human activities. Because of this strong coupling between the biogeochemical cycle of carbon 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).

During most of the Holocene, the biosphere was in approximate steady state with the atmosphere: on average, the biosphere absorbed approximately as much carbon dioxide from the atmosphere through photosynthesis as it released by respiration and by the decomposition of the dead organic material produced. However, in the 1980s, the measurements revealed that the biosphere was tending to be a net carbon dioxide sink. This net uptake partly balances the anthropogenic CO_2 emission (*Cao et al.*, 2002). Currently, less than half of the anthropogenic emission (fossil fuel burning, cement industry, deforestation, etc.) remains in the atmosphere increasing the greenhouse effect. Some 50 – 60% of the anthropogenic emission is taken up by the oceans and the terrestrial biosphere (*Denman et al.*, 2007). However, it is poorly known where and why the biospheric carbon dioxide uptake has increased. In a similar manner, we do not know how the biosphere will behave in the future.

The climate related behavior of the biosphere has been extensively studied all over the world. At present the European efforts are coordinated by the CarboEurope Integrated Project (IP) (http://www.carboeurope.org) financed by the 6th R+D Framework Programme of the European Commission. The primary aim of the project is to determine and constrain the European carbon dioxide budget with an accuracy of as high as possible on the basis of direct field measurements and application of ecosystem models. In addition to the present authors, other Hungarian scientists also participate in the project.

Most models used in CarboEurope-IP are of coarse spatial resolution, and more importantly they only use general parameterization for specific plant functional types uniform in the entire European region (*Janssens et al.*, 2003, 2005; *Vetter et al.*, 2007; *Gervois et al.*, 2008). To achieve a higher accuracy in the carbon dioxide budget estimation, the special features of smaller geographical regions should also be taken into account.

Information on the emissions and removals by certain elements of the biosphere is also collected annually for an increasing number of countries by the United Nations Framework Convention on Climate Change (UNFCCC) in the so-called national greenhouse gas inventory reports. In these reports, internationally approved methodology by the IPCC (*IPCC*, 1997, 2003, 2006) or peer-reviewed national methodologies must be applied. However, reports under the UNFCCC and, especially, its Kyoto Protocol may include only partial estimates for the terrestrial biospheric emissions and removals, while it is the *total* carbon dioxide budget that affects the CO_2 concentration of the air.

Hungary has also submitted her annual reports for almost two decades. However, although these reports take account of the vast majority of emissions and removals, not the whole budget is covered. The verification of these estimates is also necessary. In this verification, alternative methodologies and data sets should be used.

The present work is an attempt for the estimation of the *total* biospheric carbon dioxide balance of Hungary. For this purpose, the BIOME-BGC process oriented ecological system model (version 4.1.1) was adapted to the Hungarian conditions. The model results are compared with those CarboEurope results that can be related to Hungary, with the national land use dependent inventory data reported to UNFCCC, and with the Hungarian anthropogenic emission.

2. The BIOME-BGC model and its adaptation

BIOME-BGC was developed for the description of biosphere-atmosphere exchange of carbon dioxide, water, and nitrogen (*Running* and *Coughlan*, 1988; *Running* and *Gower*, 1991; *Running* and *Hunt*, 1993; *White et al*., 2000; *Churkina et al*., 2003; *Hidy et al*., 2007). BIOME-BGC can simulate the biogeochemical cycles in evergreen and deciduous forests, shrubs, and grasses. The different ecological systems need different parameter values, thus, the model should be adapted to the systems studied (*White et al*., 2000). The model also needs meteorological data, geographical and soil parameter values as input data, because these parameters convey the environmental constraints and conditions to the ecological systems. In order to use BIOME-BGC for the simulation of the carbon balance of large areas, the internal model parameters (ecophysiological parameters) are held constant, while the spatially varying soil and geographical parameters, and the temporally varying meteorological data are supplied to the model to reflect regional differences in the functionality of the different ecological systems. This assumption is only feasible if the spatial variability of the ecophysiological parameters is expected to be low. In case of Hungary, due to the relatively uniform climate, this assumption seems reasonable.

For the determination of the biospheric carbon dioxide balance, the area of Hungary was covered by a grid of $1/6 \times 1/6$ degree spatial resolution. The fraction of the different plant functional types and the characteristic soil type and weather condition were determined for each grid cell.

The determination of the land cover type is based on the CORINE CLC50 database (http://www.fomi.hu/corine/clc50_index.html). CLC50 was compiled based on satellite images taken between 1998 and 1999. It means that the spatial distribution of the different land use types is subject to uncertainty due to continuous land use change activities (reforestation, afforestation, land abandonment, etc.). Our modeling approach does not take into account the changes in land use during 2000–2007. CLC50 distinguishes among 78 land cover types. BIOME-BGC, similarly to the other models of the same kind, cannot distinguish among so many different land cover types because of the necessary simplifications and generalizations in the models (mostly caused by our insufficient knowledge and computing capacity). Therefore, the 78 different land cover types were aggregated into four basic, essentially different, categories: grasslands, agricultural fields, deciduous and coniferous forests (*Fig. 1*). The four general categories cover 81.83% of the country's area (agricultural fields: 52.95%, grasslands: 10.42%, deciduous forests: 16.72%, coniferous forests: 1.74%). The rest of the country's territory is covered by artificial land cover types (roads, built-up areas) and open water surfaces (lakes, rivers). Those areas are not handled by the model, therefore, in the present study they are considered as carbon neutral surfaces in biological sense. It does not mean that those areas are not important in the carbon cycle (e.g., anthropogenic emission can take place in the built-up areas, waters can take up or release carbon, etc.).

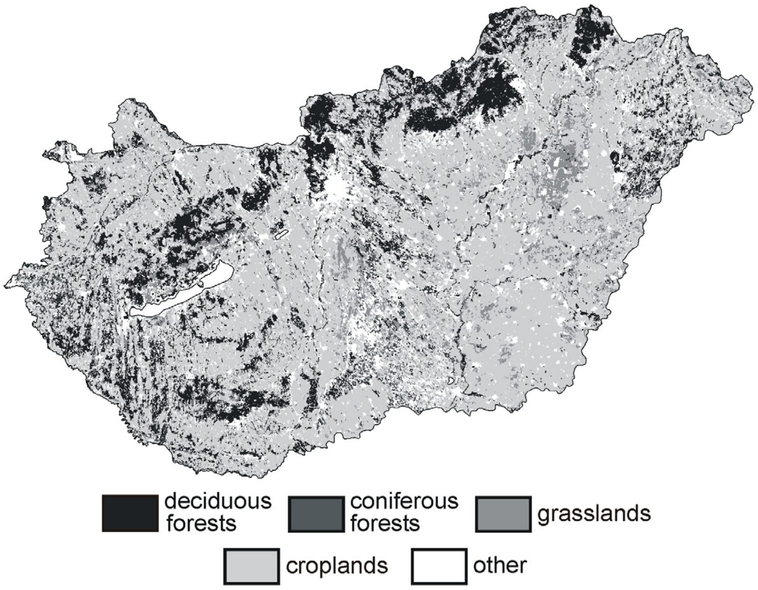

Fig. 1. Aggregated basic land cover types of Hungary used for the BIOME-BGC simulations. The map is based on the CORINE CLC50 land cover classification. Note that coniferous forests are hardly visible due to their small fraction and scattered geographical distribution.

BIOME-BGC and other process oriented biogeochemical models simulate the carbon dioxide exchange between the biosphere and atmosphere. The horizontal carbon transport (export or import of products, harvest, manure, or other carbon related materials from/to the territory studied) modifies the calculated geographical distribution of the balance. This type of geographical redistribution can be taken into account by means of additional calculations if needed (e.g., *Ciais et al.*, 2007). The results presented here are the carbon dioxide balance formed exclusively by the local biogeochemical processes (photosynthesis, respiration, chemical decomposition) and do not involve any horizontal transport. For the geographical distribution of the full carbon budget, the anthropogenic influence should be taken into account as part of the anthropogenic activity (burning of local/imported biomass, consumption of local/imported agricultural products, export/import of decomposable biospheric product/organic material, etc.). It should be noted that the model can only simulate the effects of the anthropogenic interventions (e.g., deforestation, afforestation, reforestation, irrigation, harvesting, herbage, other types of land management) on the carbon dioxide exchange in a rather limited way. Therefore, the model results are rather uncertain on recently disturbed, converted, or non-typically used lands.

Usually, the consistent biogeochemical data set required by a model is not available because of the lack of certain measurements, sampling and analytical errors, limited representativeness of the measurements, etc. Inconsistency in the input data causes transients in the beginning of the model runs not reflecting any real process, or phenomenon. The spin-up phase of the model run is used for the elimination of these transients. The only purpose of this phase is to transform the original, inconsistent input data into a consistent, steady state data set to be used for the actual simulation.

In the spin-up phase, the processes of a long (usually several decades long) period is simulated during which the soil-vegetation system reaches a steady state. This is one of the reasons why the model is unable to produce realistic carbon dioxide exchange data on recently and significantly disturbed lands.

For the spin-up the 1901–2000 period was used for which the basic meteorological data were available from the CRU TS 1.2 database (Climatic Research Unit [CRU], University of East Anglia) (*New et al.*, 2002). This database contains monthly average temperature, diurnal temperature range, and precipitation amount data on the same grid we use. For the preparation of the daily meteorological data (daily maximum and minimum temperature, daily precipitation) required by the model, a statistical weather generator (C2W) was used (*Bürger*, 1997). The missing daily meteorological parameters (average daytime temperature, average daytime vapor pressure deficit, average daytime global radiation) were generated by the MTCLIM model (*Thornton et al.,* 2000).

In the normal phase of the carbon dioxide exchange modeling (2002–2007), the grid-interpolated measurements of the Hungarian meteorological network were used. The interpolated data fields were produced by the Hungarian Meteorological Service applying the MISH method (http://www. cosis.net/ abstracts/ EGU05/07310/EGU05-J-07310.pdf).

Using the default, generalized parameter set of BIOME-BGC, the model approximates the carbon dioxide exchange of the different ecological systems with moderate accuracy. However, significantly better results can be achieved if the model is adapted to the real Hungarian conditions, that is the model is "calibrated". In the case of croplands and grasslands, the calibration was performed using Hungarian measurements (*Barcza et al.*, 2003; *Haszpra et al.*, 2005; *Nagy et al.*, 2007), while for deciduous and coniferous forests – in the lack of Hungarian measurements – the parameters were taken from the literature (*Pietsch et al.*, 2005).

In case of grasslands, measurements from three Hungarian monitoring sites (Bugac, Hegyhátsál, Szurdokpüspöki) were used. At all sites the biosphere-atmosphere exchange of carbon dioxide is directly measured using eddy covariance technique (*Barcza et al.*, 2003; *Haszpra et al.*, 2005; *Nagy et al.*, 2007). The calibration procedure of BIOME-BGC is published in the paper of *Hidy et al.* (2007).

The carbon exchange of crops is inherently affected by management practices (sowing, harvest, fertilization, etc.) that strongly influence the carbon, water, and nitrogen cycling through the ecosystem. Harvest causes a sudden drop in the standing biomass and alters the different carbon pools (aboveground biomass, litter), which in turn affects the carbon balance and the physiological response of the ecosystem to the environmental conditions. The current version of BIOME-BGC is unable to simulate disturbance and cropland management. However, considering larger regions where both winter and summer crops are present, the annual cycle of net ecosystem exchange (NEE) becomes more or less balanced in time (i.e., there is no sudden decrease in the NEE caused by harvest), as it is obvious from the large scale eddy covariance data measured over a mixed agricultural area in Hungary (*Haszpra et al.*, 2005; *Figs. 5* and *8*). The main cause of the balanced behavior is the conjoint presence of winter crops (e.g., winter wheat, harvested around June-July) and summer ones (e.g. corn, harvested around October–November). The measurement data suggest that the overall carbon balance can be approximated with the carbon dynamics of a perennial herbaceous ecosystem. In this sense, croplands can be handled as semi-natural grasslands without any sharp decrease in the standing biomass (thus, no modification in the model logic is needed for the simulation). This is the reason why BIOME-BGC can be used to simulate agricultural NEE with reasonable accuracy and handles crops as a kind of "super grass" (i.e., fertilized grass, see *Vetter et al.*, 2007) using the existing internal grass parameterization. This logic makes it imperative to use accurate measurement data for the calibration of the model to simulate super grass NEE in order to provide estimates that are comparable with the measured real cropland NEE. In Hungary the dominant land cover type is agriculture, thus, the success or failure of the present modeling activity strongly depends on the quality and proper use of the training data set.

The drawback of this grassland approach is the likely overestimation of NEE (higher CO_2 release) for the dormant season. The cause of this likely bias comes directly from cropland management: as part of the biomass is removed via harvest, it cannot decompose in the field and respire back to the atmosphere. In the model the biomass removal is not handled, thus, respiration is overestimated. As a consequence, the cropland NEE data presented here might be considered as an upper limit for cropland carbon balance.

The only monitoring project producing CO_2 net ecosystem exchange data for mixed agricultural fields in Hungary is carried out at Hegyhátsál (*Haszpra et al.*, 2001, 2005). The eddy covariance system installed at 82 m elevation above the ground has been providing regional scale NEE data since 1997. As the mosaic type mixed agricultural activity (including a mixture of winter and summer crops) can be considered typical in a large part of Hungary, the data measured here can be used for the calibration of BIOME-BGC (using the grass submodel) for the general Hungarian conditions. 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; *Haszpra et al.*, 2005). 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 ($R^2 = 0.72$).

There are no Hungarian measurements available for deciduous and coniferous forests, therefore, the model calibration cannot be performed as it was implemented for grasslands and croplands. We used the data of *Pietsch et al.* (2005) recommended for BIOME-BGC. Their parameter sets were determined on the basis of measurements in oak (*Quercus robur/petraea*) and Scotch pine (*Pinus sylvestris*) forests. The measurements were carried out in low elevation regions of Austria and Czech Republic close to Hungary, where the climatic conditions are similar to those in Hungary.

Although oak is the dominant species among the Hungarian deciduous trees, significant areas are covered by Black locust (*Robinia pseudoacacia*) and other species. Thus, the generalized application of the oak parameter set may be considered as an oversimplification to characterize all Hungarian deciduous forests, but the parameterization cannot be refined without measurements on other species yet.

A better parameterization could be achieved using Hungarian forest inventory data (see, e.g., *Somogyi*, 2007), however, the calibration methodology for BIOME-BGC is not developed yet.

In summary, the main simplifications of our modeling approach are as follows: (a) BIOME-BGC is applied mainly to disturbed ecosystems, though the model logic is not prepared yet for the precise description of managed ecosystems; (b) the ecophysiological parameters for the different plant functional types are held constant during the simulation; (c) agricultural ecosystems are handled as "super grass", which means that harvest is not simulated but the annual course of NEE is well represented; (d) only a very limited number of tree species are simulated (oak and pine) in the lack of information about the spatial distribution of tree species and also in the lack of ecophysiological parameters for some of the other relevant tree species; (e) BIOME-BGC cannot simulate the effect of pests and diseases, and the long-term consequences of extreme weather events are not accounted for either; (f) the CLC50 database might be outdated due to land use change activities that are occurring in Hungary, which causes uncertainty in the simulation. Future research is essentially needed to address the above mentioned limitations of our modeling methodology.

3. Results

Using the input data and parameter sets presented above, the total Hungarian net biosphere-atmosphere CO_2 exchange has been calculated using daily time steps for 2002–2007 by means of BIOME-BGC. In the atmosphere-oriented studies like the present one, the net biospheric carbon uptake is denoted by negative sign, because the amount is a loss from the point of view of the atmosphere. Data are given in carbon amount throughout the paper (1 g C = 3.67 g CO_2, or 1 g CO_2 = 0.27 g C).

Fig. 2 shows the 6-year mean annual cycle of NEE for the different plant functional types averaged for all grid points. It can be seen in the figure, that the model captured the seasonal variation of the carbon exchange of the biosphere in all cases. On average, each plant functional type acts as a net carbon sink during the growing season (except for coniferous forests during July and August). Cropland NEE is balanced in time according to the modeling philosophy (super grass), that is in accordance with the measurement data (*Haszpra et al.*, 2005). Grassland carbon uptake decreases in time during the growing season because of its higher sensitivity to drought. These results are in accordance with the field evidence (*Barcza et al.*, 2003; *Nagy et al.*, 2007). During the dormant season, the ecosystems are net sources of CO_2, although for croplands it might be somewhat overestimated by the model (see above). Ecosystem respiration is the highest for deciduous forests probably due to decomposition of the high amount of organic matter. Respiration of coniferous forests is relatively low during the dormant season.

The daily data were aggregated for each year, for each grid cell, and for the entire area of Hungary taking into account the spatial extent of the different plant functional types in each individual grid cell. The annual sums of NEE for the different land cover types are presented in *Table 1* and also in *Fig. 3*. The data suggest that croplands are usually sources of carbon dioxide, grasslands are net sources or net sinks, while forest areas are usually net sinks. The balance shows that biosphere is a net source in Hungary. It seems that, on country level, the forests and croplands are the largest sinks and sources, respectively, but the contribution of grasslands must not be neglected, either.

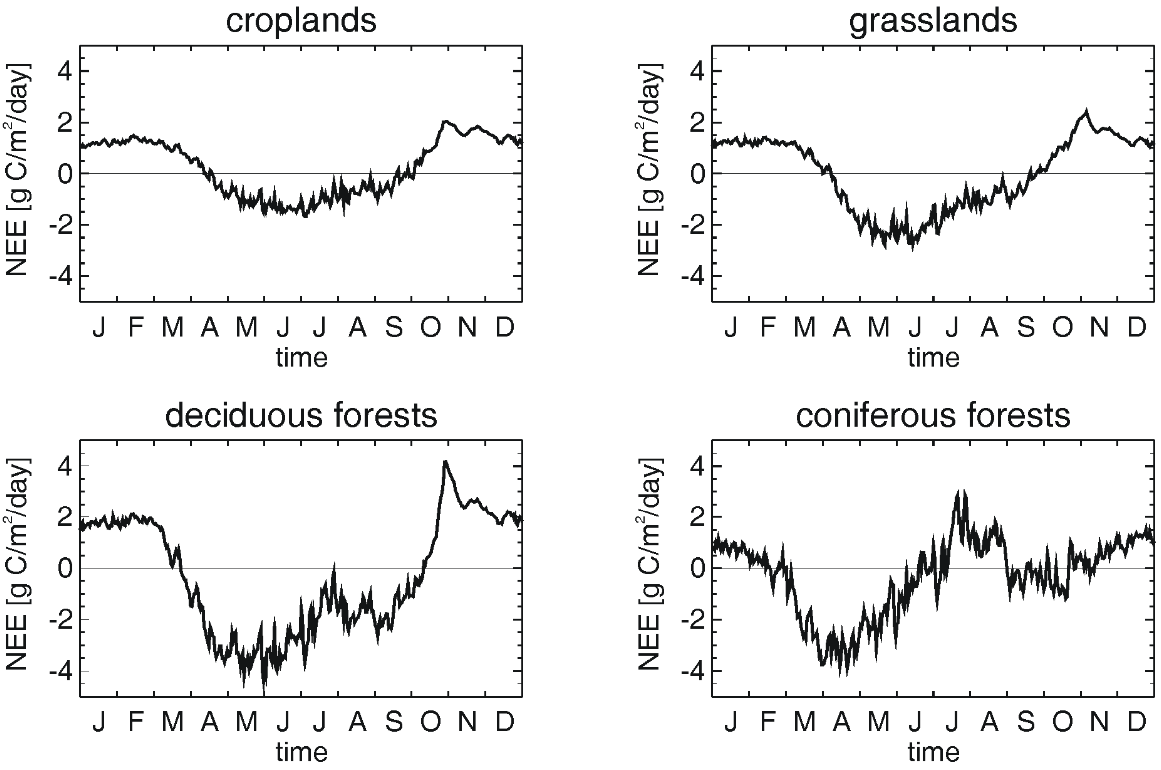

Fig. 2. Six-year mean annual cycle of modeled net ecosystem exchange of the different plant functional types averaged for all grid points. Negative NEE indicates carbon uptake by the vegetation.

Table 1. Biospheric carbon dioxide balance of Hungary estimated by the BIOME-BGC model for the time period of 2002–2007 (Mt C/year). Negative values indicate carbon uptake by the vegetation

	2002	**2003**	**2004**	**2005**	**2006**	**2007**
Croplands	5.12	4.06	4.92	5.55	4.85	3.86
Grasslands	-0.08	0.80	-0.60	-0.55	-0.94	0.32
Deciduous forests	-2.05	0.96	-3.09	-3.49	-3.40	-1.02
Evergreen coniferous forests	-0.18	0.08	-0.32	-0.25	-0.18	-0.12
Total	**2.81**	**5.90**	**0.91**	**1.26**	**0.33**	**3.04**

Our aim was not only to determine the average NEE but also to get information on the range of interannual variability (*Fig. 3*). The climate fluctuations significantly influence the activity of the biosphere and, thus, also its carbon balance. The climate variation in the study period (2002–2007) offered a unique possibility to study the effect of these fluctuations. 2003 was an extremely hot and dry year, which ended a long, increasingly warm and dry period followed by cooler and wetter years.

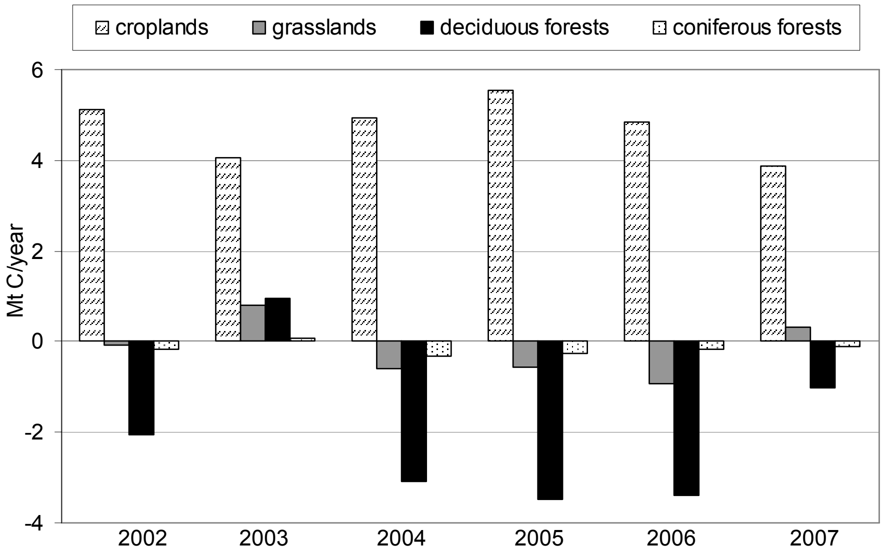

Fig. 3. Biospheric carbon dioxide exchange of the different land cover types for the entire country between 2002 and 2007 (Mt C/year) calculated using BIOME-BGC. Negative values indicate carbon uptake by the vegetation.

exchange data of the four basic land cover types for 2003 and 2004 (for two years with contrasting weather conditions, *Figs. 4* and *5*) show that agricultural fields were net carbon dioxide sources in both years, whereas grasslands were net sources in 2003, but net sinks in 2004 under the more favorable environmental conditions. These results are in accordance with the measurements presented in *Nagy et al.* (2007). In 2003, all ecological systems lost significant amount of organic material due to the extremely hot and dry weather.

The forests, storing a high amount of carbon, reacted more sensitively to the significant climate deviation than the agricultural fields and grasslands (*Figs. 4* and *5*). Except for the higher, cooler and wetter regions of the northern mountainous part of Hungary, both deciduous and coniferous forests were net carbon dioxide sources in 2003. In a significant area of the country the emissions exceeded 300 g C/m^2/year. However, in 2004, which was significantly cooler, and wetter than 2003, they became sinks at a similar rate.

Fig. 6 shows the annual mean biospheric carbon dioxide balance of Hungary for the entire study period (2002–2007). The figure was created from the BIOME-specific simulated NEE data taking into account the spatial extent of the specific land cover types for each grid cell. The figure shows that CO_2 uptake is generally associated with the forested areas (cf., *Fig. 1*). During 2003, almost the entire country became a net carbon dioxide source, only the mountainous regions in Northern Hungary and some other areas in Western Hungary acted as net sinks. It is interesting to see that in 2007, the western part of Hungary became an almost homogeneous net source, similarly to 2003.

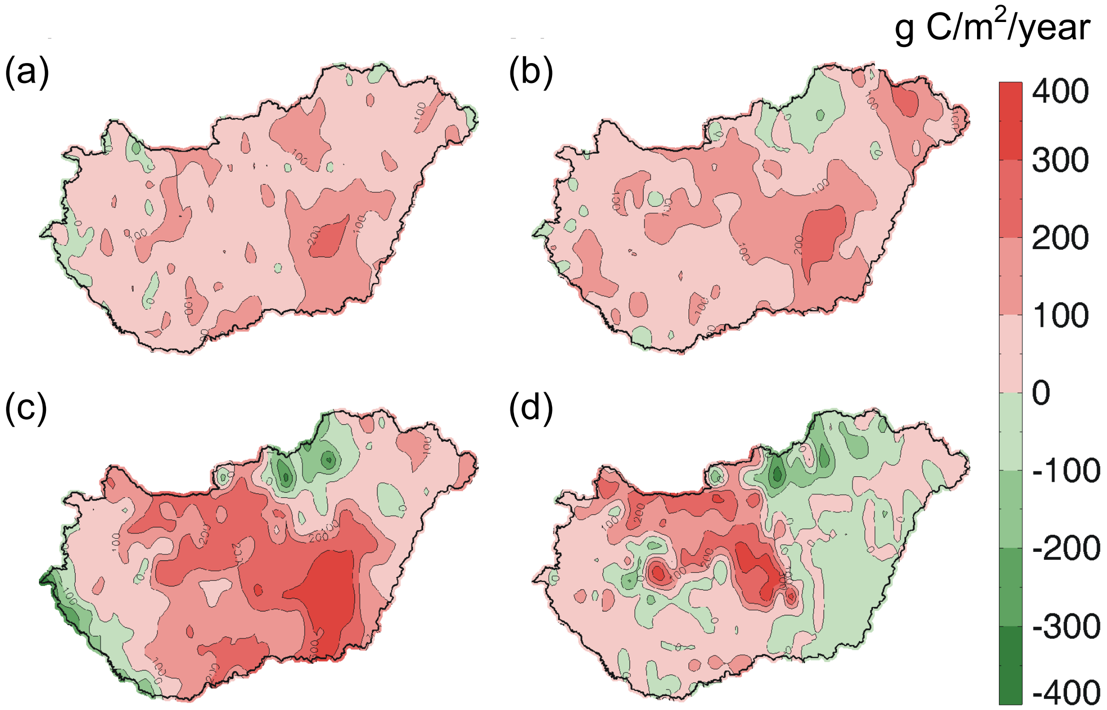

Fig. 4. Net carbon dioxide exchange of the different land cover types in 2003 (g C/m^2/year) estimated by the BIOME-BGC model. Negative values indicate carbon uptake by the vegetation. (a) croplands, (b) grasslands, (c) deciduous forests, (d) coniferous forests. Note that the numbers are only applicable where the specific plant functional types are present (see Fig. 1).

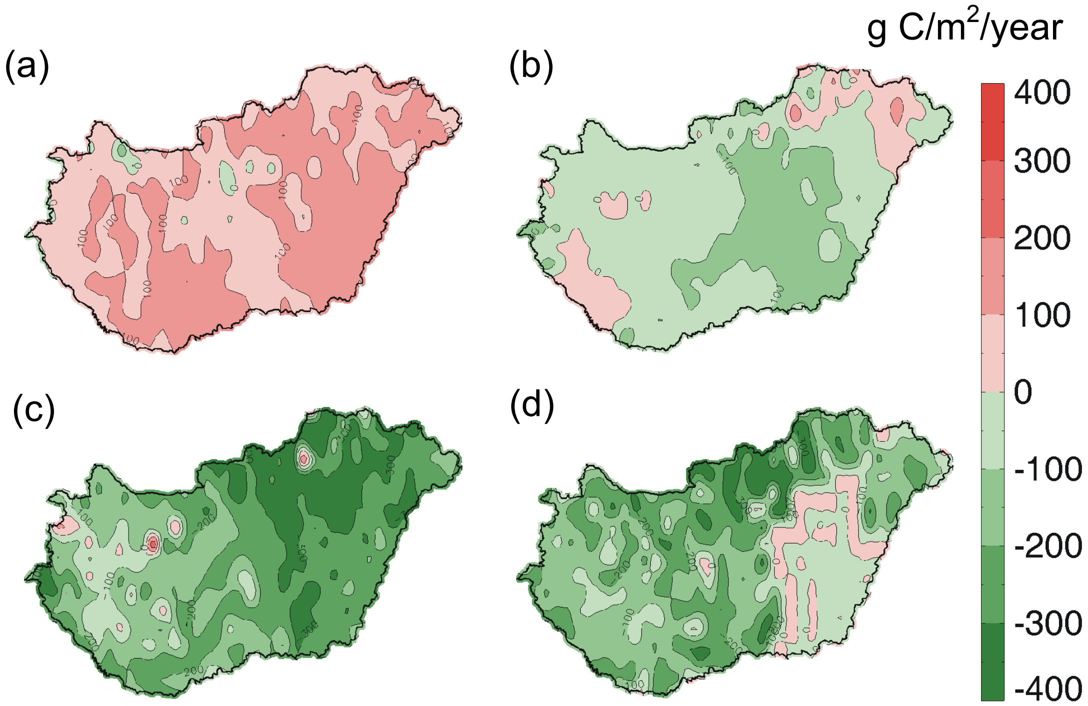

Fig. 5. Net carbon dioxide exchange of the different land cover types in 2004 (g C/m^2/year) estimated by the BIOME-BGC model. Negative values indicate carbon uptake by the vegetation. (a) croplands, (b) grasslands, (c) deciduous forests, (d) coniferous forests. Note that the numbers are only applicable where the specific plant functional types are present (see Fig. 1).

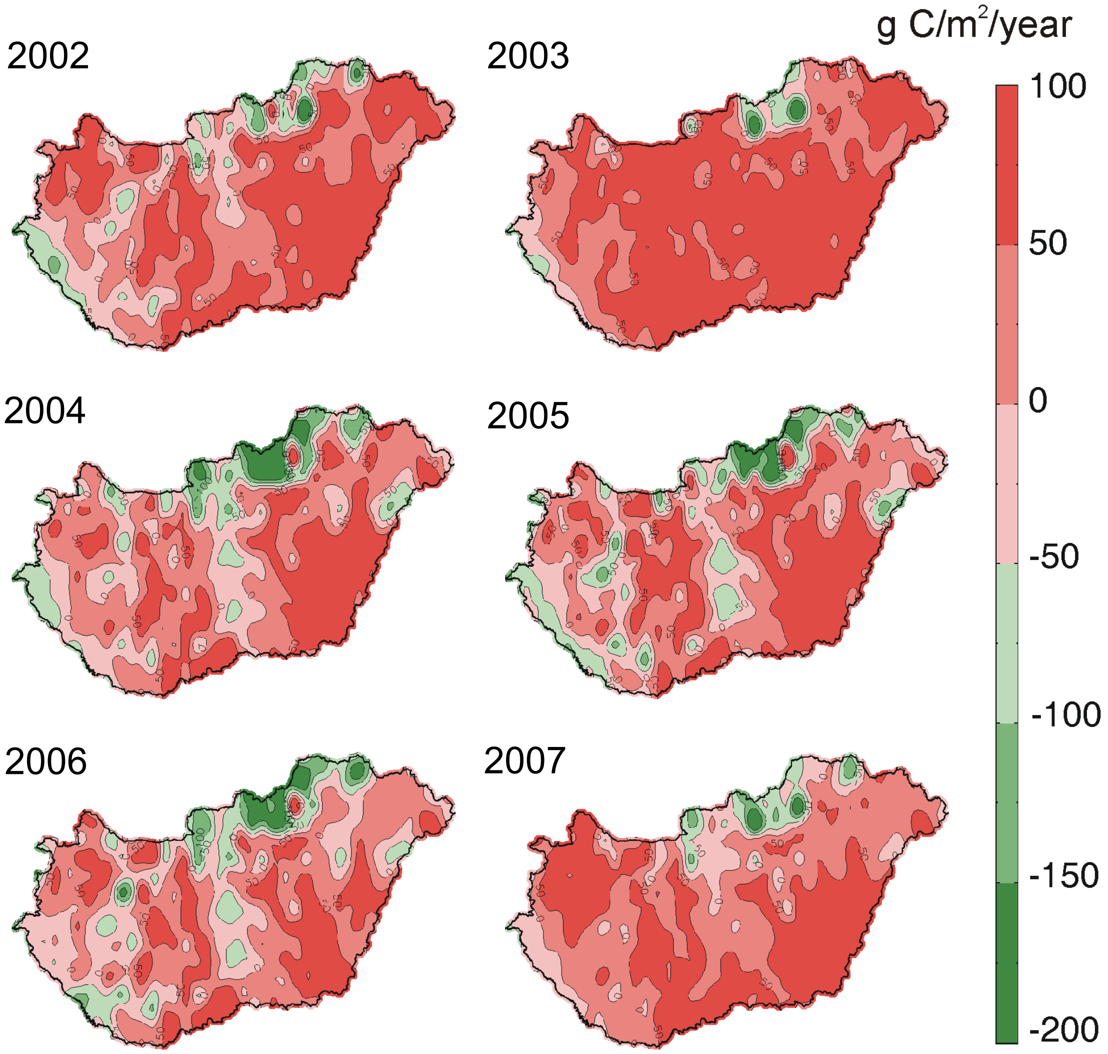

Fig. 6. Mean biospheric carbon dioxide balance of Hungary for the entire study period (2002–2007) estimated by the BIOME-BGC model (g C/m^2/year). The simulated, BIOME-specific NEE data were weighted for each grid cell. Negative values indicate carbon uptake by the vegetation.

4. Discussion

The model estimates in this study show that the net carbon dioxide balance of Hungary is positive, i.e., that the soil-vegetation system is a net carbon dioxide source on national level (*Table 1*). Its main cause is the significant net release from the agricultural fields. Any change in the ratio of the agricultural and forest areas would modify the biospheric carbon dioxide balance.

The model estimates were compared with the data reported by Hungary to the UNFCCC (*HMS*, 2008; see also *UNFCCC*, 2006). Under the UNFCCC, Hungary reported emissions of –0.76, –5.44, 0.24, –0.85, and –0.01 kt C/year for 2002, 2003, 2004, 2005, and 2006, respectively, for croplands and grasslands together, which are much lower emission estimates than those calculated by BIOME-BGC. On the other hand, Hungary reported net removals of 0.86, 1.31, 1.11, 1.58, and 1.27 Mt C/year for forests, which are considerably lower than those estimated by BIOME-BGC. At the same time, it is known that BIOME-BGC may tend to overestimate the annual net CO_2 release of croplands, but quantification of this likely overestimation needs further research. Some of the differences are due to known discrepancies in methodology. The IPCC deals with the estimation of greenhouse gas emissions and removals from human activities and takes into account yearly changes in land use instead of using one land use database. Accordingly, carbon stock changes on *managed land* in the relevant carbon pools are reported under the IPCC methodology that exludes reporting on unmanaged land, which is only required when unmanaged land is subject to land use conversion. As regards forests, Hungary reported under the UNFCCC the change only in biomass carbon pool, while soil and dead organic matter carbon pools have not been reported yet due to lack of appropriate databases. In cropland and grassland categories the changes in soil carbon pool are reported which are influenced by changes of the way land was used (abandonment of croplands and pastures, afforestation of croplands and grasslands, and tillage practices). In accordance with the IPCC methodology, the change in biomass in cropland category is estimated only for perennial woody crops. (The results of the sequestration of perennial woody biomass were not taken into account in the comparison.) For annual crops, the increase in biomass stocks in a single year is assumed to be equal to biomass losses from harvest and mortality in the same year. Thus, there is no net accumulation of biomass carbon stocks on cropland by the IPCC methodology under default assumptions. In grassland, where management practices are static, biomass carbon stocks are in an approximate steady-state, so the change in biomass carbon pool is neglected as well. Even though there are differences between the methodology of the IPCC and the model approach, this comparison clearly suggests that further studies are needed to identify the possible causes of the major differences. Due to the simplified methodology and limited data bases of both approaches, both the BIOME-BGC and the IPCC-based inventory approach should be analyzed and developed to harmonize estimates.

Fig. 7 shows the national biospheric carbon dioxide balance calculated by us and *Janssens et al*. (2005). Janssens and his coworkers (*Janssens et al*., 2005) used a completely different approach: they estimated carbon budget based on changes in the carbon stocks, which means that they did not estimate biospheric NEE but the stock change. Of course NEE is related to the C stock change both in forests and croplands. In spite of the different methodology, their results are close to ours, though they only gave an overall value for the period studied. 2003 cannot be considered a typical year, therefore, its inclusion or exclusion significantly influences the 2002–2007 average.

It can be seen in *Fig. 7* that the significant net CO_2 release of the agricultural fields is remarkable in both cases. Because of the high share of the agricultural fields in the national net carbon dioxide balance and the related uncertainty in the model performance, the study of the agricultural carbon cycle could be an important target of the Hungarian research.

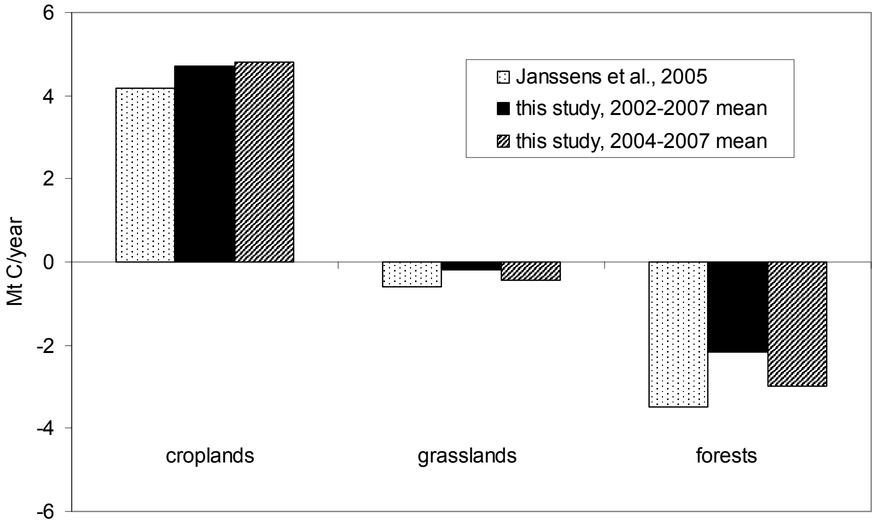

Fig. 7. Biospheric carbon dioxide balance of Hungary based on the country specific run of BIOME-BGC (present study), and on the data provided by *Janssens et al.* (2005). Negative values indicate carbon uptake by the vegetation. 2003 can not be considered a typical year (see text), thus, its inclusion or exclusion influences the average balance.

In order to illustrate the order of magnitude of our model results, it is interesting to mention that in the 2002–2005 period, the mean total anthropogenic carbon dioxide emission of Hungary, excluding emissions and removals from land use, land-use change, and forestry, was 60.75 million tons CO_2 (16.57 Mt C) (*HMS*, 2008). According to the model calculations presented, the biosphere in Hungary adds 8.7 million tons of CO_2 to this amount every year on average (2002–2007 mean) with significant interannual variation: the highest net emission was calculated for 2003 (21.6 Mt CO_2), while the lowest for 2006 (1.2 Mt CO_2).

Although forests sequester a significant amount of carbon dioxide, their CO_2 uptake may decrease or disappear with the warming climate, as it was experienced in 2003. According to the model results, the prevailing weather dramatically and rapidly influences the carbon dioxide exchange, i.e., the CO_2 uptake of the biosphere. This finding is supported by the measurements at Hegyhátsál where the net CO_2 exchange of the mixed agricultural lands changed significantly, from +69 g C/m^2/year (source) to –107 g C/m^2/year (sink) from 2003 to 2004 (*Haszpra et al.*, 2005).

Grasslands and forests are usually net carbon dioxide sinks. However, the uptake does not necessarily mean long term carbon storage. A large portion of the carbon dioxide taken up by croplands and grasslands may quickly return to the atmosphere through the consumption of the biomass by humans or animals. The total amount of carbon dioxide taken up by the forests is not stored in the forests forever either: the carbon content of the forest vegetation also returns into the atmosphere sooner (from firewood or due to disturbances) or later (from harvested wood products like furniture, buildings, other construction materials). The above mentioned processes must be taken into account in order to provide a full carbon budget of the biosphere. The extension of the present study with the quantitative estimate of horizontal carbon transport may provide a useful tool for constraining the total carbon budget of Hungary.

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