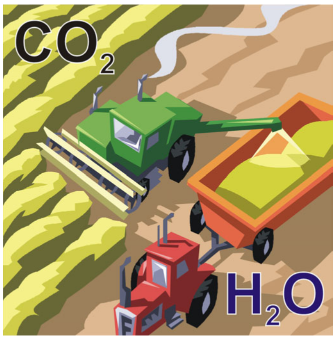
MEASURING AND MODELLING WATER AND CARBON BALANCE OF MANAGED AGRICULTURAL LANDS (OTKA K104816)



FINAL REPORT

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Table of contents

1. Introduction

Carbon cycle related research is of central importance due to the well-recognized feedback between the terrestrial carbon balance and global climate change (Friedlingstein and Prentice, 2010; Ciais et al., 2013). Research dealing with the terrestrial carbon balance was traditionally focused on forests. Less is known about the carbon balance of herbaceous vegetation including agricultural lands (grasslands and croplands; Gervois et al., 2008; Ciais et al., 2010). Large uncertainty can be attributed to the difficulties of state-of-the-art models to adequately describe management and the water and carbon balance related processes in the soil (Sándor et al., 2016a,b; Vuichard et al., 2016).

One essential component of the terrestrial carbon balance is soil organic carbon (SOC). Soil quality has a strong relation with SOC (Reeves, 1997; Lal, 2004). Soils with high SOC content have generally higher quality and have better soil water holding capacity due to the large humus content, which result in higher crop yield (Lal, 2004). If agricultural lands are losing carbon (as it is suggested by recent studies; Barcza et al., 2010; Kutsch et al., 2010), it means that soils are under degradation. Some studies indicate that current management practices are responsible for the carbon loss from agricultural sector due to the disturbance of the soil surface and decrease of carbon input into the soil (Gervois et al., 2008; Tóth et al., 2010). There is a well-recognized possibility to introduce environment-friendly practices in agriculture to prevent soil degradation and to improve soil quality (Smith et al., 2001; Lal, 2004). Management practices such as minimum tillage or no tillage can potentially improve soil structure and quality, though their role in agricultural productivity and greenhouse gas emission mitigation is questionable (VandenBygaart, 2016).

Measurement of the water and carbon balance components are thus essential to improve our understanding of the functioning of agricultural lands (Haszpra et al., 2005; Barcza et al., 2009b; Kutsch et al., 2010; Tóth et al., 2010) and to clarify the role of environmental conditions and management on the crop yield and greenhouse gas balance. Though measurements are expensive and labour intensive, their availability is crucial for the spatial extension and generalization of the results on country or continental scale.

Besides field measurements, mathematical models constructed for the detailed description of soil processes and plant growth are essentially needed to estimate the long term response of agricultural lands to the changing environmental conditions and management practices (Ciais et al., 2010; Friedlingstein and Prentice, 2010; Hidy et al., 2012). The currently available, soil respiration and carbon balance related models have been developed for different purposes, therefore they are optimized to simulate processes on different temporal scales and provide a more or less sophisticated description of soil processes and carbon fluxes (Herbst et al., 2008). Therefore, combining the advantages of these models can improve carbon balance estimations. However, we can only rely on models that are capable to reproduce the present day water and carbon balance of the agricultural ecosystems with acceptable accuracy. Thus, continuous development and evaluation of the models are essential. Research projects that cover both measurements and modeling exercise are of great importance because of the bi-directional relationship between measurements and model application.

The overarching goal of the OTKA K104816 project was to decrease uncertainties in carbon and water balance estimations of agricultural lands in Hungary. We planned to achieve these goals by evaluating and improving the available models that can be used to simulate crop yield, soil water content and carbon balance components of agricultural lands in Hungary. In the frame of the project the emphasis was on evaluating three models having different approaches: the Biome-BGC (Barcza et al., 2008, 2009a, 2010), the 4M (Fodor et al., 2002; Fodor and Kovács, 2005; Fodor and Pásztor, 2010; Fodor et al., 2012) and the HYDRUS-1D SOILCO2. Model evaluation was performed based on reference data (soil water content, soil respiration and ecosystem scale carbon balance component) measured at two Hungarian experimental sites (Hegyhátsál and Józsefmajor Experimental and Demonstration Farm). As part of the work, data demand of the models led us to the creation of a climate database called FORESEE that is one major outcome of the project. Another major achievement is the development and dissemination of the Biome-BGCMuSo v4.0 model created with the combination of the models used in the project. Performance tests were done with the 4M, Biome-

BGCMuSo and HYDRUS-1D models with specific settings related to soil disturbance and management. The original workplan submitted with the project proposal is presented in Appendix I.

2. Experimental sites

The research was primarily focused on two experimental sites in Hungary: on the Józsefmajor Experimental and Demonstration Farm, and on Hegyhátsál. Selection of the sites was justified by the ongoing research programmes (Tóth et al., 2012). Additional simulations were performed for the whole country using 4M (Fodor et al., 2002; Fodor and Kovács, 2005; Fodor and Pásztor, 2010; Fodor et al., 2012) and Biome-BGCMuSo (Hidy et al., 2016). Here we provide a basic site description for Józsefmajor and Hegyhátsál.

2.1. Józsefmajor Experimental and Demonstration Farm (JEDF)

Static chamber soil CO_2 efflux (soil respiration), soil water content (SWC) and soil temperature measurements have been carried out at Józsefmajor Experimental and Demonstration Farm (JEDF) of Szent István University. The site is situated in Northern Hungary nearby the city of Hatvan (47° 41' 31.7"N, 19° 36' 36.1"E, 110 m asl). The annual average precipitation is 580 mm (662 mm in 2014), ~320 mm of which falls in the vegetation period. The soil type is chernic calcic chernozem developed on loamy clay, which is common in this part of the country.

A long-term tillage/climate experiment was initiated at JEDF in 2002, where the following six different soil tillage treatments were applied: mouldboard ploughing (P), deep cultivator, shallow cultivator, disking, loosening+disking, and no tillage (NT). All plots are rainfed so that the differences in their performance in different years can be monitored. Every treatment has four spatial replicates in a randomized pattern. Apart from tillage type, the applied management is identical at the experimental plots in any other aspects (no irrigation, uniform fertilization, pesticide/herbicide application).

We carried out chamber measurements once per week during the vegetation period from 2013 to 2016. Additional measurements were done in the dormant season with lower frequency. Due to the high labour requirement of the measurements, two treatments – tillage systems causing the least (NT) and most (P) soil disturbance – have been selected for monitoring. Descriptive characteristics of the soil in the selected two treatments are shown in Table 1. CO_2 sampling was carried out simultaneously in the ploughing and no tillage treatments between 9 and 11 AM local time in 7 spatial replicates. After the sampling, CO_2 concentrations were determined by a gas chromatograph equipped with flame ionization detector (FISONS 8000).

Table 1. Soil characteristics in the ploughing and no-till treatments in JEDF long-term tillage/climate experiment.

Soil properties	**Ploughing**		**No tillage**	
	0-5 cm	**5-10 cm**	**0-5 cm**	**5-10 cm**
pH (KCl)	5.96 ± 0.72	5.57 ± 0.05	4.92 ± 0.03	4.69 ± 0.12
pH (H_2O)	6.88 ± 0.48	6.61 ± 0.04	5.85 ± 0.03	5.68 ± 0.14
Total N [%]	0.16 ± 0.03	0.18 ± 0.00	0.25 ± 0.00	0.21 ± 0.02
NH_4-N [mg kg^{-1}]	7.30 ± 2.81	10.23 ± 0.51	7.30 ± 2.20	8.17 ± 2.20
(NO_2+NO_3)-N [mg kg^{-1}]	3.21 ± 1.01	4.67 ± 1.02	5.26 ± 0.88	3.50 ± 0.88
Organic C [%]	1.58 ± 0.37	1.77 ± 0.03	2.28 ± 0.08	2.08 ± 0.06
SIR [μg CO_2-C g soil^{-1} h^{-1}]	1.24 +- 0.40	1.11 ± 0.03	1.80 ± 0.40	1.15 ± 0.21
Humus [%]	2.73 ± 0.63	3.06 ± 0.06	3.92 ± 0.14	3.59 ± 0.10
Bulk density [g cm^{-3}]*	1.20 ± 0.09		1.38 ± 0.05	
Sand fraction (2-0.05 mm) [%]*	10.20		10.27	
Silt fraction (0.05-0.002 mm) [%]*	53.41		55.69	
Clay fraction (<0.002 mm) [%]*	36.38		34.04	

* data from April 09, 2014.

To examine the environmental conditions of the site, soil water content and soil temperature sensors (5TM Decagon Devices Inc., Pullman, WA USA) were installed at 5 different depths at the sampling area. Meteorological data were collected nearby JEDF in the city of Heréd at a private weather station (published on http://wunderground.com). Additional data were provided by the Hungarian Meteorological Service.

Leaf area index (LAI) was measured in 2015 and 2016 using a handheld ceptometer (Accupar LP-80, Decagon Devices Inc., Pullman WA USA). In 2016 vegetation season regular measurements of plant height, dry weight and stem diameter were initiated and green LAI was also determined using a leaf/root scanner (Delta-T Scan Root Analysis System, Delta-T Devices, Burwell, UK) to serve as a reference for ceptometer estimations. Upon harvest, grain yield, straw and root mass are routinely determined in each treatment. Yield data were recorded in every year together with root and straw/stem measurements after harvest.

2.2. Hegyhátsál

The unique, double eddy covariance (EC) system is operated on a tall tower (82 m above the ground), and next to the tall tower (in the grass-covered garden of the tower), at village Hegyhátsál, West Hungary (Vas county, 46°57'N, 16°39'E, 248 m asl; Haszpra et al., 2001). The climate of the Hegyhátsál region is temperate continental. The long-term average (1961-1990) annual precipitation in the region is around 750 mm, while the average temperature is 8.9 °C. During the measurement period mean annual temperatures were higher, while annual precipitation amounts were generally lower than the long term means. The soil type in the region is '*Lessivated brown forest soil*' (Alfisol, according to USDA system; Haplic Cambisol according to the WRB classification). The organic matter content of the upper 15 cm thick layer is 1.3-1.9%. The soil texture is loam/silt loam.

Hegyhátsál 1 cropland site

The EC measurements at 82 m height started in 1997. The monitoring was temporarily interrupted in 2000 for technical reasons, but it was continuous afterwards. Initially the system consisted of an ultrasonic anemometer (Solent Windmaster, Gill Instruments Ltd., Lymington, United Kingdom), an aspirated fine wire thermocouple (Model ASPTC, Campbell Scientific Ltd., Loughborough, United Kingdom) and a fast response infrared CO_2/H_2O analyzer (LI-6262, Li-Cor Inc., Lincoln, Nebraska, USA). In 2002 the ultrasonic anemometer was replaced with a new model (Gill R3-50, Gill Instruments Ltd., Lymington, United Kingdom) also capable to measure the virtual temperature, thus the thermocouple was removed from the system. Measurements are made at 4 Hz. Air is sucked through the sampling tube and the analyzer at about 15 L min^{-1} resulting in turbulent flow in the whole system. Pressure fluctuations generated by the pump are damped by means of a 6 L buffer volume (Haszpra et al., 2001). For details on the ancillary measurements and on the calibration procedure applied at Hegyhátsál see Haszpra et al. (2001; 2005).

The eddy covariance measurement installed at 82 m height represents the carbon balance of a mixture of croplands (mainly maize and winter wheat; see Barcza et al., 2009b) and some other land cover types. Thus, the measured GPP and R_{eco} cannot be associated to winter wheat and maize exclusively, but can be used to assess the overall ability of the model to represent magnitude of fluxes. The results are representative to a mixture of croplands, which is typical in Central Europe.

Hegyhátsál 2 grassland site

The low elevation EC measurement (at 3 m) was established in the garden of the tower over a managed, species rich, semi-natural grass field (hay meadow) surrounded by agricultural fields. The area of the site was used as arable land previously and was turned into grassland around 1990. The dominant species of the grassland are *Arrhenatherum elatius, Taraxacum officinale, Poa pratensis, Agropyron repens, Anthoxanthum odoratum*, *Dactylis glomerata*, *Holcus lanatus, Briza media* and *Festuca pratensis.* The grass is mowed two times a year, and the mowed grass is taken away from the site and utilized as fodder.

The monitoring system was originally based on a Li-Cor Model LI-6262 closed path, fast response infrared gas analyzer and a three dimensional, fast response sonic anemometer-thermometer (Kaijo-Denki, model DA-60; 1999-2000; see Barcza et al. 2003). Due to malfunction of the anemometer, the measurements were ceased in 2001. In 2006, the measurements were resumed when the ultrasonic anemometer was replaced with a new model (Gill R3-50, Gill Instruments Ltd., Lymington, United Kingdom). The sonic anemometer and the inlet tube of the IRGA are mounted on a mast at 3 m elevation above the grass-covered surface. The inlet tube is mounted at the elevation of the active center of the ultrasonic anemometer, 25 cm away from it horizontally. Raw voltage data generated by the fast response sensors were collected and digitized by means of a TEAC data logger between 1999 and 2000, while since 2006 the digital signals of the sensors have been recorded by a PC also at 5 Hz frequency.

Soil water content measurements were started in September, 2001, using a Campbell CS615 water content reflectometer (Campbell Scientific, Inc., Logan, Utah, USA). Soil water content is measured as the mean SWC in the 15-30 cm soil layer. Detailed description of the ancillary measurements can be found in Haszpra et al. (2005).

3. Measurement results

3.1. Józsefmajor Experimental and Demonstration Farm

Long-term agricultural experiments can provide unique information on the contrasting effects of the applied management practices. The complex interactions in the soil-plant-atmosphere system can be studied from various aspects especially related to soil functioning and degradation. At the JEDF study site, a rather sophisticated crop rotation was applied during the measurement period (2013-2016). Details on the crops sown and timing of the most important management events are listed in Table 2.

Table 2. Management details at JEDF tillage/climate experiment (TBA: to be announced).

Year	Tillage date	Sowing date	Seed type	Harvest date	Growing season (days)
2013	28/09/2012	08/03/2013	**Spring barley** (Scarlett)	19/07/2013	132
2014	21/10/2013	14/04/2014	**Sunflower** (P63LE75)	25/09/2014	162
2015	02/10/2014	08/10/2014	**Winter wheat** (Antonius)	08/07/2015	272
2016	28/10/2015	18/04/2016	**Maize** (LG 33.30 (FAO 340)	TBA	TBA

To examine the effect of the applied management systems on plant productivity we measured several parameters such as grain yield, root biomass, straw/stem weight. Table 3 shows these parameters for each year.

Fig. 1 shows soil respiration during the observation period. Vegetation period (from sowing to harvest) is highlighted with coloured boxes. According to this graph soil respiration increases in the first part of the vegetation period every year. Roots are not excluded from the measurement plots, so the results reflect the significant contribution of autotrophic (root) respiration to the measured soil CO_2 efflux. CO_2 emission was higher in the no-tillage treatment than that in the ploughing in most of the cases (113/57 times), but it must be noted that the uncertainty is very high (as reflected by replicated measurements), therefore the difference between the two treatments is not statistically significant in many sampling days.

Table 3. Plant biomass and yield data at the JEDF tillage/climate experiment (TBA: to be announced).

Year	Crop	Grain yield (t/ha)		Root biomass (t/ha)		Straw/stem weight (t/ha)	
		ploughing	no tillage	ploughing	no tillage	ploughing	no tillage
2013	**Spring barley**	2.945	2.897	1.55	1.82	2.42	2.38
2014	**Sunflower**	3.230	2.186	2.99	2.28	3.88	2.52
2015	**Winter wheat**	5.70	4.82	1.16	1.11	5.58	4.49
2016	**Maize**	TBA	TBA	TBA	TBA	TBA	TBA

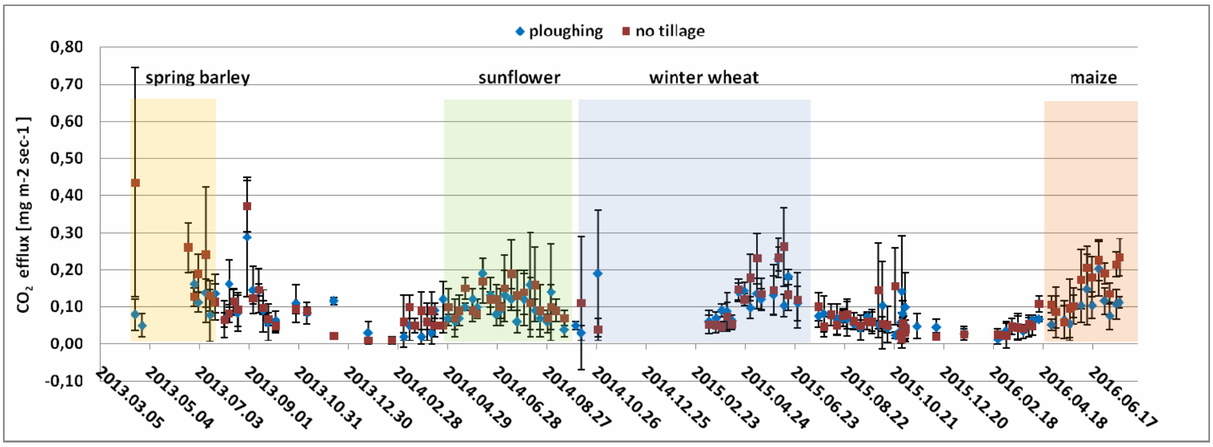

Figure 1. Result of the soil respiration measurements at JEDF during the OTKA project. Ploughing and no tillage related results are shown together.

Several studies examined the short term effect of tillage (soil disturbance) on soil CO_2 emission (Marquina et al., 2014; Silva-Olaya et al., 2013; La Scala et al., 2006). In the frame of the project, we also aimed at the separation of the immediate and long-term effect of soil disturbance represented by tillage application. Hence, beside regular measurements during the vegetation period, we investigated the variations in CO_2 emission right after ploughing in two field measurement campaigns in 2013 and 2015 performed in the ploughing and in the no-till treatments. The relationship between the two treatments examined during the vegetation period reverted after the tillage. The results show that after the tillage event ploughing has higher soil respiration compared to the no tillage treatment in almost every case, but it must be noted that the differences are not significant.

Continuous monitoring of soil moisture in case of agricultural fields is not an easy and trivial task due to management events that regularly disturb measurements, and represent serious risk of damaging the instrumentation. Hence, long-term monitoring efforts in agricultural areas are rare in the country especially considering different tillage practices although there is an increasing demand from the scientific community on the international level for reliable soil moisture observations.

SWC time series often contain erroneous data as a result of e.g. disturbance (management events), instrument failure, low voltage etc. Obviously false data originating from identified causes (e.g. removal/disturbance of sensors) is filtered based on visual inspection, while an additional automatized quality check was performed based on Dorigo et al. (2012). The raw SWC and soil temperature data were post-processed to obtain daily average values. Capacitance based soil moisture measurements are shown to be sensitive to soil temperature changes (e.g. Chansy et al., 2012), and the most common method to correct for temperature dependency is temporal averaging. The accuracy of soil moisture measurements and sensor calibration equations vary among soil types (Kinzli et al., 2012, Seyfried et al., 2005), generally measurements are more accurate on sandy than on clayey soils. At JEDF the soil type is rather clayey; therefore a soil specific calibration of the soil water content/temperature sensors have been carried out for the upper and lower soil layers, separately, for both treatments. According to manufacturer's recommendations, calibration is more dependent on soil type than on individual sensors, as sensors are identical in construction.

Soil water content time series for the two full years of measurements are shown in Fig. 2. We show here only the two upper levels (5-10 cm and 15-20 cm depth) for the ploughing treatment, which are the most relevant regarding soil CO_2 emission. Daily average values were calculated only if more than 60% percent of the data for that particular day was available. Larger data gaps occurred at management events when soil probes had to be removed and during dormant season when measurements were sometimes unreliable due to low soil temperatures. Instrument failure (data logger in the ploughing treatment) also limited our data amount. Drying of the upper layers of the soil is visible in both years, although one can identify the effect of large convective precipitation events as well. The same trends were observed in the direct drilling (NT) treatment, but overall the upper soil layers in the P treatment were dryer than in the direct drilling.

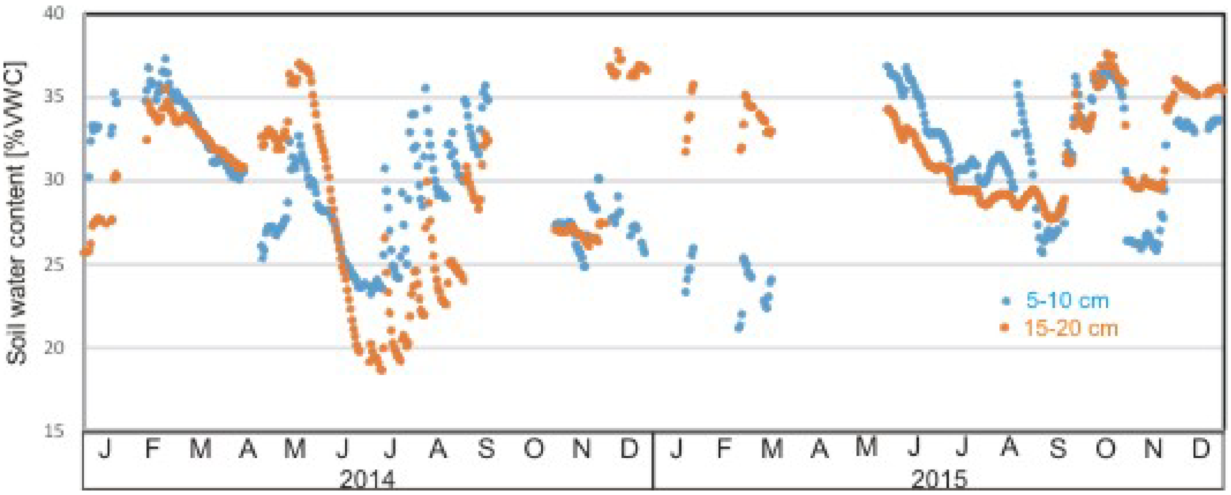

Figure 2. Soil water content in the upper two layers at the ploughing treatment in two consecutive measurement years at JEDF.

3.2. Hegyhátsál

Operation of the eddy covariance measurements was quasi-continuous during the time frame of the project (September, 2012 – August, 2016). The eddy covariance system that is operational above the grassland (at 3 m height) had a larger data gap (due to failure of the timer controlling valves) during November-January, 2013, so annual sums were not calculated for 2013.

High frequency, raw eddy covariance data was processed and evaluated using published methods (Barcza, 2001; Barcza et al., 2003; Haszpra et al., 2005; Barcza et al., 2009b). The calculated Net Ecosystem Exchange of CO_2 (NEE) was separated into Gross Primary Production (GPP) and Total Ecosystem Respiration (R_{eco}) using standard methods. Gap filling was performed to create simulated data for the missing measurement intervals (see Barcza et al., 2009b for details; note that gap filled data was not used for model evaluation). The calculated fluxes are available at 30 min (3 m) and at 60 min (82 m) resolutions to the scientific community on request. The data are further processed into daily and annual sums. Basic meteorological data that was provided by the Hungarian Meteorological Service is also available for the interpretation of the data.

In this report only the annual sums of NEE are presented for simplicity. Fig. 3 shows the annual NEE sums for the tall tower system representing mixed agricultural fields. Fig. 4 shows the same for the grassland. It is obvious that variability of the ongoing weather caused striking interannual variability of NEE for both systems. Note that for the 82 m height system NEE was negative for all years during the OTKA project, which means that the ecosystem acted as a net sink of CO_2 from the atmosphere. Note that these data do not include lateral carbon fluxes (harvest and other activity).

Interestingly, the positive NEE that was representative to the pre-OTKA time period in 2001, 2002 and 2003 never occurred since 2004.

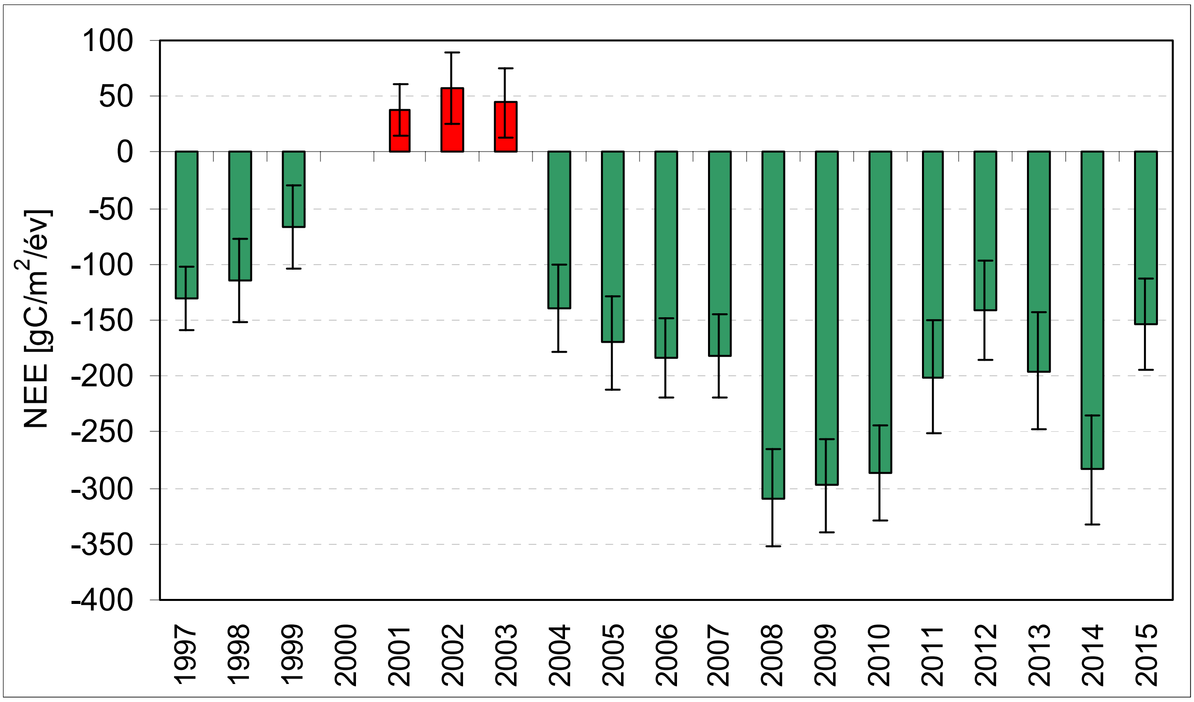

Figure 3. Annual NEE sums for Hegyhátsál, based on the eddy covariance system operational at 82m height. Negative NEE means carbon uptake from the atmosphere.

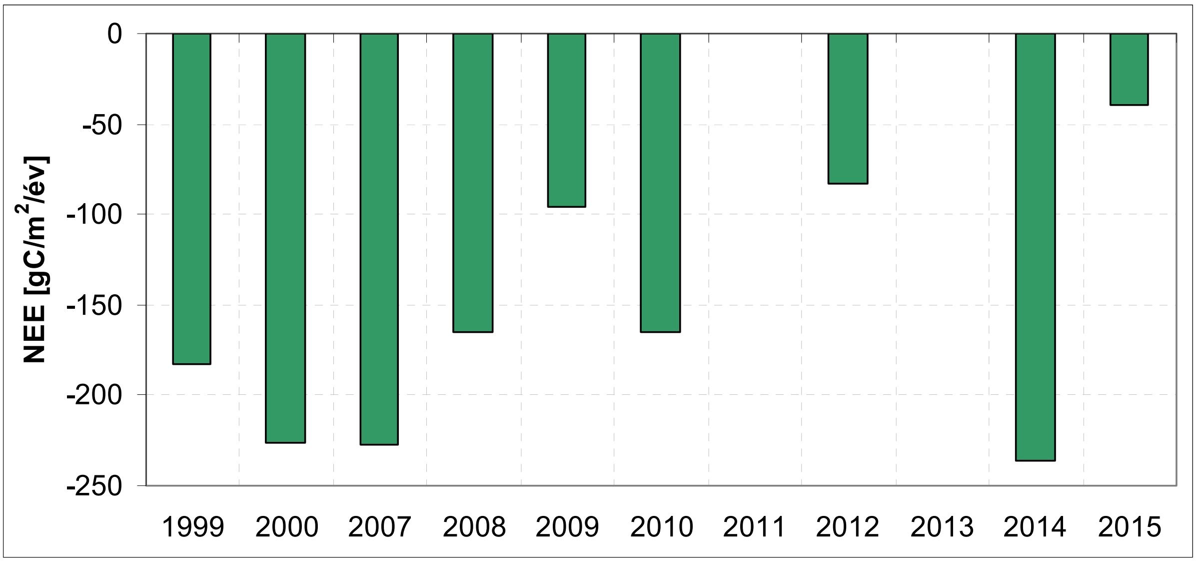

Figure 4. Annual NEE sums for the grassland that is located in the garden of the Hegyhátsál tall tower. Negative NEE means carbon uptake from the atmosphere.

4. Climate database construction

Meteorological data are essentially needed for the modeling activity, typically with a daily time resolution. Due to the lack of appropriate datasets that can be used for country-scale simulations, we decided to construct a new database within the frame of the OTKA K104816 project.

For the past, observation based gridded datasets can be used, while for the future regional climate model (RCM) results can be post-processed (Giorgi, 1990). The raw climate model results always contain inherent systematic errors as a result of uncertainties in the parameterization and climate model structure (Christensen et al., 2008). Such data may be unusable for impact studies which, typically, need unbiased climate data, as the models are sensitive to biases in the driving meteorological data (Baigorria et al., 2007). The assumption that systematic errors in the future are propagated equally to the past (Maraun, 2012) allows for using various bias correction methods (Ines and Hansen, 2006; White and Toumi, 2013)

The newly constructed, open access climate database that was created within the project is called FORESEE (Open Database **FOR** Climat**E** Change-Related Impact **St**udies in C**E**ntral **E**urope; http://nimbus.elte.hu/FORESEE/; Dobor et al., 2015). This database covers the 1951-2100 time period with daily time steps. The FORESEE contains observation-based data for the past based on the daily E-OBS (Haylock et al., 2008) and the monthly CRU TS 1.2 datasets (Climatic Research Unit, University of East Anglia, UK; Mitchell et al., 2004). For the future ten different regional climate model results were used, which were disseminated within the ENSEMBLES FP6 project (Van der Linden and Mitchell, 2009) assuming the SRES A1B greenhouse gas emission scenario (IPCC, 2000). A cumulative distribution function fitting method (also known as quantile mapping/fitting or histogram equalization) was used for the temperature and precipitation correction based on the 1951-2009 period (Dobor et al., 2015; Ines and Hansen, 2006; Dosio and Paruolo, 2011). The climate model results and the observation based datasets were compared. Based on the monthly comparison correction factors were defined. These correction factors are then applied to the daily climate model results for the past and also for the future. In case of the temperature, the correction means shifting, while in case of rate of precipitation it means multiplication. The correction of the precipitation frequency was also executed. The target area of the database is Central Europe, with a horizontal resolution of 1/6×1/6 degree. The Hungarian grid points of the FORESEE grid were used for the crop modeling study.

The FORESEE dataset is accessible through its website (http://nimbus.elte.hu/FORESEE/) in NetCDF file format, where additional information about the dataset is also available. A questionnaire-based survey (Dobor et al., 2015) indicated that NetCDF format is not usable for most responders, and Microsoft Excel-compatible data (i.e. pure text retrieval of data) would be the most suitable. To meet this demand, the web service technology was used to enable easy access to data for the users. A map based query site provides tailored access to the database at http://nimbus.elte.hu/FORESEE/map_query/index.html. A query has to be formulated according to the geographical location, requested meteorology variables, time interval in years (from 1951 to 2100), and selection of RCM, if time range is over the observational period. The service finds the corresponding FORESEE grid cell and serves the requested dataset in comma separated ASCII text format.

The FORESEE database is updated from time to time for the past time period. The up-to-date version of the FORESEE is the 2.1, where the 1951-2014 period is covered by observations. Documentation of the construction of FORESEE is available in an open access, peer reviewed journal (Dobor et al., 2015).

5. Model developments

The main aim of the proposed research was to evaluate and improve the available models that can be used to simulate crop yield, soil moisture content and carbon balance of agricultural lands in Hungary. In the original workplan it was planned that HYDRUS-1D SOILCO2, Biome-BGC, ANTHRO-BGC and 4Mx would be used.

During the project, it became clear that application of ANTHRO-BGC is not preferred as it contains features that were not suitable for our purposes (issues were found in the fertilization submodel). Therefore, we decided that we merge Biome-BGC and ANTHRO-BGC and create a much more flexible model also addressing the fertilization handler issue. Experiences gained during the application of 4M, plus studying the theoretical basis of 4M we implemented several features into

Biome-BGC taken directly from 4M. As a result, the models that we used in the project were 4M, HYDRUS-1D SOILCO2 and Biome-BGCMuSo, where the latter is the developed version of Biome-BGC and the product of the OTKA team.

In this sense, one major achievement of the OTKA K104816 project is the development and dissemination of the Biome-BGCMuSo biogeochemical model. Developments were also made for the 4M model, where the missing planting day estimation method was introduced and deeply evaluated (Dobor et al., 2016).

As Biome-BGCMuSo is a milestone product of the OTKA project, we provide here brief information on the model. Biome-BGCMuSo v4.0 can simulate the carbon, nitrogen and water budget of both unmanaged and managed terrestrial ecosystems. All of our model improvements are detailed in our submitted manuscript, which is in discussion phase in Geoscientific Model Development Discussions (Hidy et al., 2016).

Some developments are described below to demonstrate the major adjustments. We implemented a special growing season index (HSGSI), and a new, dual snow cover limitation method for photosynthesis and onset of growing season. A 7-layer soil module was implemented instead of the simple bucket model. This is a major development as current crop models use several soil layers. New soil water fluxes (diffusion, percolation, runoff, pond water formation) were implemented and soil variables are calculated for each layer. The original model ignored plant wilting and associated senescence (where the latter is an irreversible process) caused by soil drought. In order to solve this problem a new module was implemented to simulate the ecophysiological effect of drought stress on plant mortality. Instead of uniform distribution of mineral nitrogen, a varying amount of mineralized nitrogen is available within the different soil layers for root uptake. To simulate the effect of management activities on the carbon, nitrogen and water pools we implemented mowing, grazing, sowing, harvest, ploughing, fertilizing, and thinning. New plant pools were implemented, such as fruit (i.e. yield) and soft stem to simulate the functioning of agricultural systems on a more realistic way. A new, enzyme-driven C4 photosynthesis routine was implemented into the photosynthesis module, which is important for maize-related simulations. Crop residue management was implemented, and the litter pool was separated into aboveground and belowground litter pools to support the inclusion of crop cover effect on soil hydrology in the future. Ploughing with different depths was implemented.

In cooperation with the Institute of Ecology and Botany, Centre for Ecological Research, Hungarian Academy of Sciences (MTA ÖK) and using support from the BioVeL European Union funded project, we created a computer-based, open infrastructure that can help a wide array of users in applying the new model. The infrastructure consists of two parts: the "Biome-BGC Projects Database and Management System" (BBGCDB; http://ecos.okologia.mta.hu/bbgcdb/), and the "BioVeL Portal" (http://portal.biovel.eu). BBGCDB and the BioVeL Portal act as a virtual research environment and collaborative tool. BBGCDB and the BioVeL portal help the sensitivity analysis and parameter optimization of Biome-BGCMuSo by a computer cluster-based Monte Carlo experiment and GLUE methodology (Beven and Binley, 1992).

We would like to support Biome-BGCMuSo application for the wider scientific community as much as possible. Therefore we created a website (http://nimbus.elte.hu/bbgc) and a detailed, comprehensive User's Guide (Hidy et al., 2015). We also published the source code of the model at GitHub (https://github.com/bpbond/Biome-BGC/tree/Biome-BGCMuSo_v4.0), which is probably the most popular repository for sharing scientific software.

6. Model characterization/benchmarking

Several test runs, measurement-model comparisons, and benchmark tests were performed during the 4 years of the OTKA project. The majority of the tests are documented as part of the internal project documentation, which is available online at http://bzoli.web.elte.hu/public/K104816/

Here we provide a brief excerpt containing some interesting results.

In one benchmarking experiment we evaluated model results and measurement data for the Hungarian cropland experimental sites in two years when the precipitation conditions were markedly different. The model simulations were done for two sites, for Hegyhátsál and Józsefmajor. The model results were compared to eddy covariance and soil water content measurements (Hegyhátsál). The FORESEE database gave the input meteorological data. The main question was: what are the simulated effects of contrasting dry and wet conditions on the different variables? Based on the records of the Hungarian Meteorological Service we chose years 2010 and 2011 for the analysis. 2010 was the wettest year in the 1901-2011 period (considering annual sums and spatial averages for Hungary), while 2011 was the driest on record. Regarding to the differences between the two extremely different years the measurements showed decreased GPP and R_{eco} fluxes in the dry year (small NEE increase) for Hegyhátsál, but the differences were quite small. Previously it was demonstrated that the effect of drought on CO_2 fluxes could be greater in case of 2-3 consecutive dry years (see Fig. 3; years 2001-2003). The results suggest that a single drought year might not cause substantial changes in the carbon balance if the previous year was characterized with ample precipitation. Comparison of measured and modelled results indicate that the model captured the magnitude of change for R_{eco}, but the decrease in GPP was not simulated well for the drier year on an annual scale.

In another benchmarking effort the effect of soil disturbance was analyzed on the simulated pools and fluxes with Biome-BGCMuSo. The simulation results indicated that, due to the developments, Biome-BGCMuSo has ability to simulate the effect of soil disturbance to some extent. Simulated fluxes and pools differed for till and no-till systems. Fig. 5 shows an example where soil water content was simulated at Józsefmajor, under conventional ploughing and no tillage.

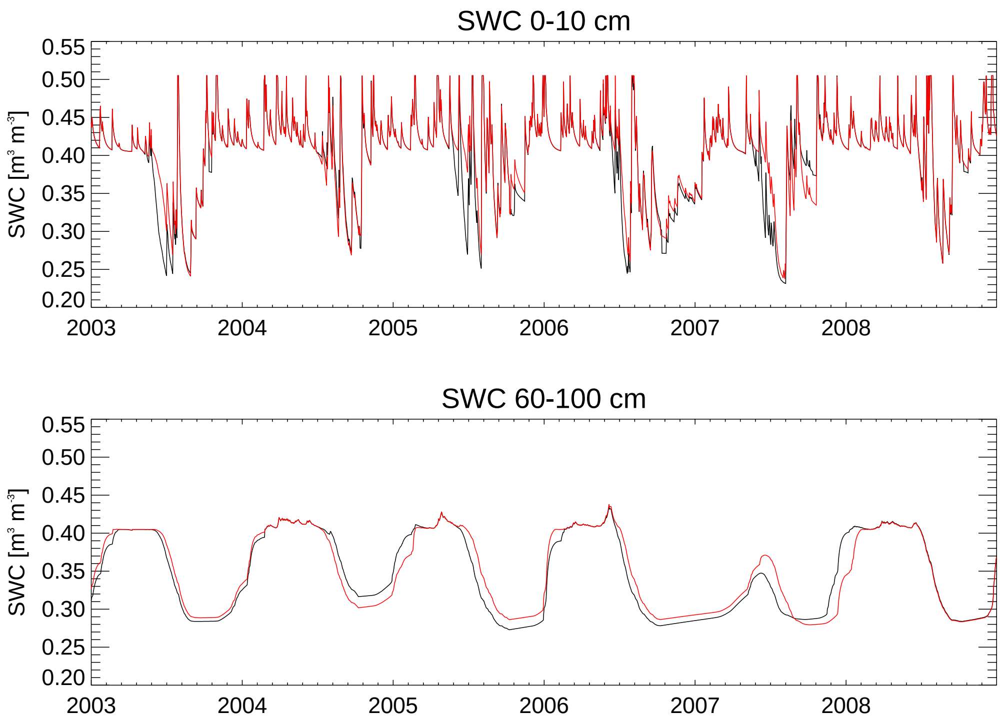

Figure 5. Comparison of simulation results for different soil layers with medium ploughing (30 cm depth; black line) and no-tillage (red line) soil management for the 2003-2008 time period.

Some of the results were contrasting for maize and winter wheat, which needs further investigation. Considering the model logic, at present the soil structure is affected by ploughing only in terms of homogenization of soil texture in the affected layers (plus homogenizations of mineralized N and soil water, but these are expected to alter the results only slightly). Alteration of soil structure due to ploughing can be set by the user in terms of bulk density and hydraulic properties. The model can be further developed to automatically handle the effect of ploughing in terms of soil properties. More data are needed from site measurements to accurately handle the soil disturbance within the models.

Nevertheless, the developed Biome-BGC MuSo v4.0 has promising capability to simulate cropland carbon balance and production.

Using the developed Biome-BGCMuSo v4.0 model we also assessed the effect of improved soil hydrology representation on the simulated soil respiration and carbon balance for the experimental sites. For Józsefmajor measurement-model comparison was based on the soil respiration data obtained in the frame of the project. The results showed that the simulation quality was improved due to improved representation of soil hydrological properties and probably due to other structural changes. For Hegyhátsál it was demonstrated that Biome-BGCMuSo v4.0 provides more realistic simulation results in terms of magnitude of fluxes than earlier model versions. In spite of the rough model averaging, and the lack of model calibration, the NEE curves are acceptable, and they show the intra-annual variation of NEE. The model could even capture the peak of NEE in the autumn, caused probably by human intervention and residue management. The results indicate the utility of the modeling framework, which was created with the support of OTKA.

The HYDRUS-1D model was also evaluated at Józsefmajor in terms of its ability to simulate soil water content dynamics. Fig. 6 shows one simulation result for the ploughed field for 2014. The figure shows that the simulations reasonably reproduced the measurements. Interestingly, Biome-BGCMuSo and other similar models typically provide SWC results where the amplitude is smaller than the observed one (Sándor et al., 2016b). This is not the case with HYDRUS-1D, which is a promising feature of the model that claims for further investigation. HYDRUS-1D faces difficulties simulating the amplitude of soil moisture content changes responding to precipitation events and soil drying during hot summer periods after harvesting winter crops. This failure is probably associated with the presence of stubble residue (approximately 80% of plants remain on the field at JEDF) affecting infiltration and evaporation processes. However, the model development and calibration to include this effect requires longer time series on soil water content and soil temperature.

On the other hand, all the simulation models work with soil hydraulic properties that are constant in time. In reality, these properties are changing considerably even under natural conditions (due to freezing-thawing cycles, soil biological activity, root development etc.), but in tilled soils these changes are even stronger. This might be partly the explanation of getting relatively better estimates for soil water content dynamics in the beginning of the simulation period (Figure 6), when the soil hydraulic properties in the model represent well the real situation in the field. Further in time, the soil structural changes lead to changes in soil hydraulic properties in the field, but these changes are not represented in the model.

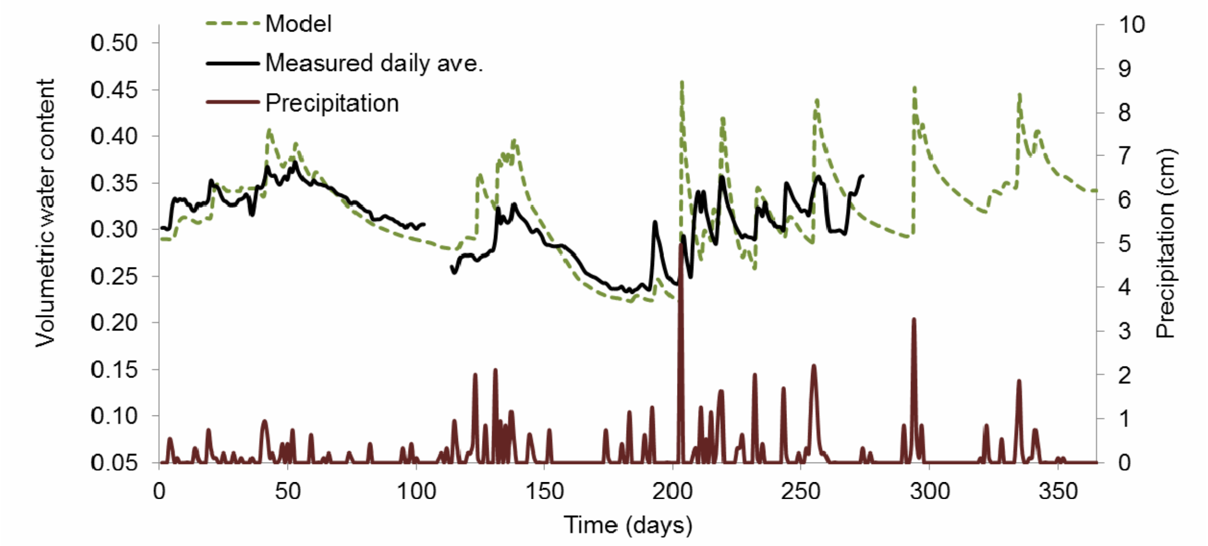

Figure 6. Average measured and simulated soil water content (SWC; m^3 m^{-3}) at 20-25 cm below the ploughed soil column.

In a novel benchmarking experiment the effect of soil texture was studied on the simulated soil properties and on crop yield. In our experiment the soil texture was altered using the same meteorological dataset and management settings. The runs were executed for two crops (winter wheat and maize) at two sites (Hegyhátsál and Józsefmajor) each with all the 12 soil texture classes used within 4M (assuming the same texture for the upper and lower layers). The managements were set representing the country scale average. Fig. 7 shows a summary of the simulations for Hegyhátsál, with several hypothetical soil textures. Simulated soil temperature did not differ significantly for the different textures. In contrary, the soil water content showed great differences. In every case sandy soils gave the smallest values while clay was the largest which is in accordance to our expectations. Evapotranspiration and crop yield were also sensitive to the choice of the soil texture. The results indicate that besides climatic conditions soil characteristics also substantially alter biomass production, thus carbon balance of croplands.

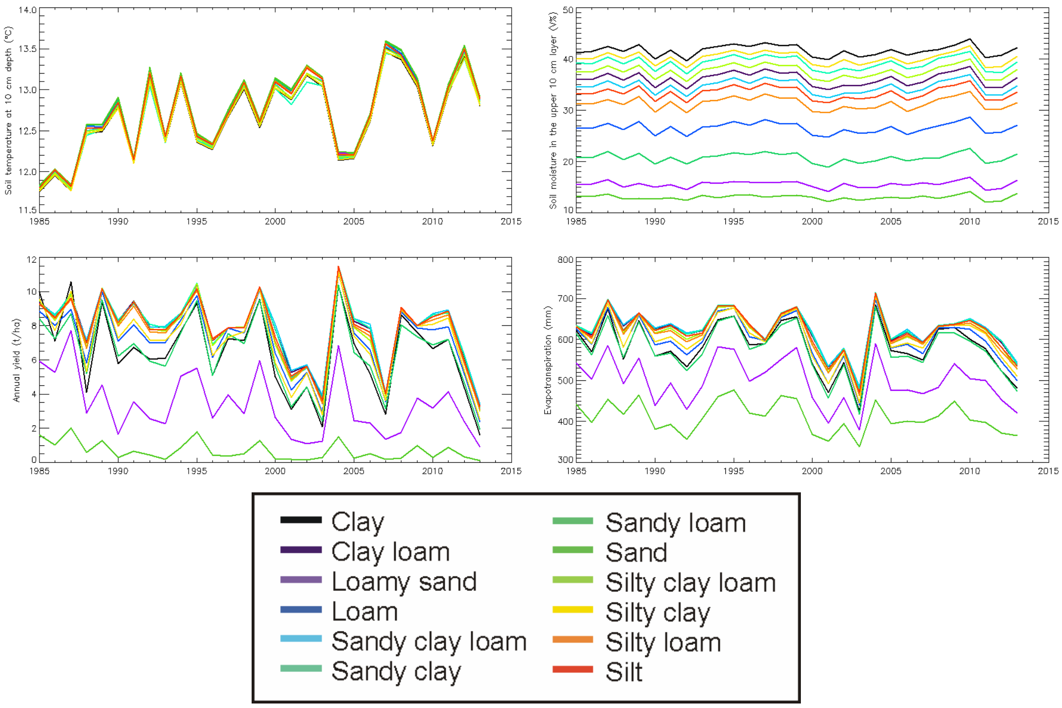

Figure 7. Soil temperature at 10 cm depth, soil water content in the upper 10 cm layer, annual maize yield and evapotranspiration for the period 1985-2013 assuming different soil textures at Hegyhátsál.

Test simulations were performed to study the effect of alternative management practices on the overall water and carbon balance of croplands. In the first simulations (reference run) it was assumed that after harvest all plant residues remain at the site (this is close to the current practice in Hungary for maize). In the alternative simulation it is assumed that 100 % of the residue is removed immediately after harvest and utilized elsewhere. These scenarios represent the two contrasting extremes for residue management, so they are useful to find differences between the results. According to the results, the leaf area index (LAI) is consistently lower for the alternative case (100 % removal of residues) as compared with the reference run (all residues are left at the site). Evapotranspiration (ET) does not differ significantly between the two cases. In contrast, gross primary production (GPP) and total ecosystem respiration (R_{eco}) are lower for the alternative case. Soil respiration, which is part of R_{eco}, is remarkably lower (by ~50 %) in the alternative case, which is consistent with the removal of biomass. Soil carbon, litter (both aboveground and belowground) amounts are lower for the alternative case. Crop yield (represented by fruit carbon) is also lower for the alternative case. These results suggest that residue management can substantially alter production and ecosystem carbon balance in the long term. The model results are consistent with the expectations in terms of reduced litter amount, and possibly subsequent lower soil organic matter (SOM) pools and associated nitrogen mineralization.

Focusing specifically on SOM, we studied the effect of alternative management using simulation results from a longer time period. Fig. 8 shows the long term (in this case 34 years) evolution of recalcitrant SOM content at Józsefmajor for the two residue management cases. (Note that Biome-BGCMuSo uses the so-called converging trophic cascade (CTC) model to simulate SOM dynamics, where 4 pools are defined. Recalcitrant SOM contributes to the majority of SOM, so here only the 4th pool is plotted keeping in mind that other small transient microbial pools are also present.) The results show that SOM decreases with time in both cases, which means that according to the model the system continuously loses carbon. If this is real, then soil quality degradation might be present, which endangers sustainable agriculture in the long run. The decreasing SOM might be the consequence of continuous yield export from the plot. Nevertheless, the figure clearly shows that 100 % removal causes faster SOM decrease.

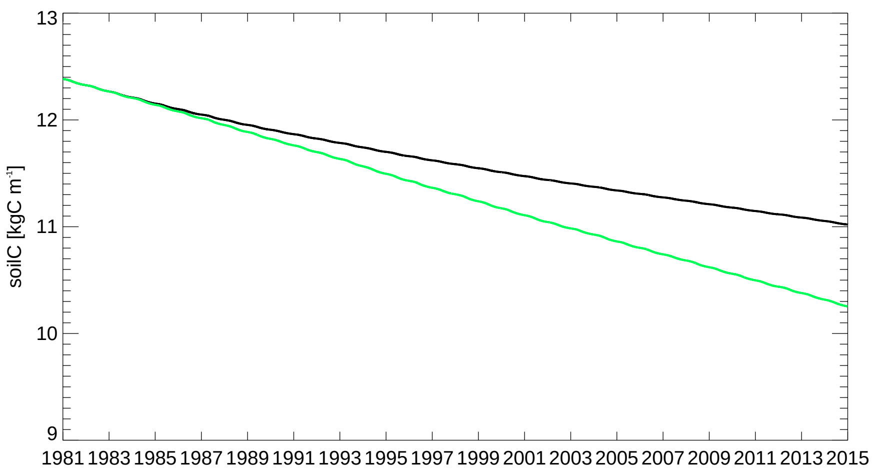

Figure 8. Effect of residue management on the long term recalcitrant soil organic matter (humus) content at Józsefmajor. Two extreme cases are compared, where black line shows the case when all residues are left at the site, and green line shows the case when all residues are removed from the site after harvest. Yield is removed completely in both cases.

Based on the simulation results it is possible to quantify the long term SOM decrease rate as a function of the residue removal. Fig. 9 shows the results of the modeling exercise. The figure shows that decadal SOM loss is a linear function of the residue removal, and SOM loss ranges between 0.39 kgC decade^{-1} and 0.63 kgC decade^{-1}. The results indicate that during a 100-year horizon the soil can lose 4-6 kgC m^{-2}, which is comparable with the overall SOM content of the site. This indicates large sensitivity of SOM pool on management decision. Note that this loss might be a pessimistic estimation as intercropping, rotation with legumes, application of organic fertilizers or other management settings might affect SOM and can result in smaller rate of SOM decrease.

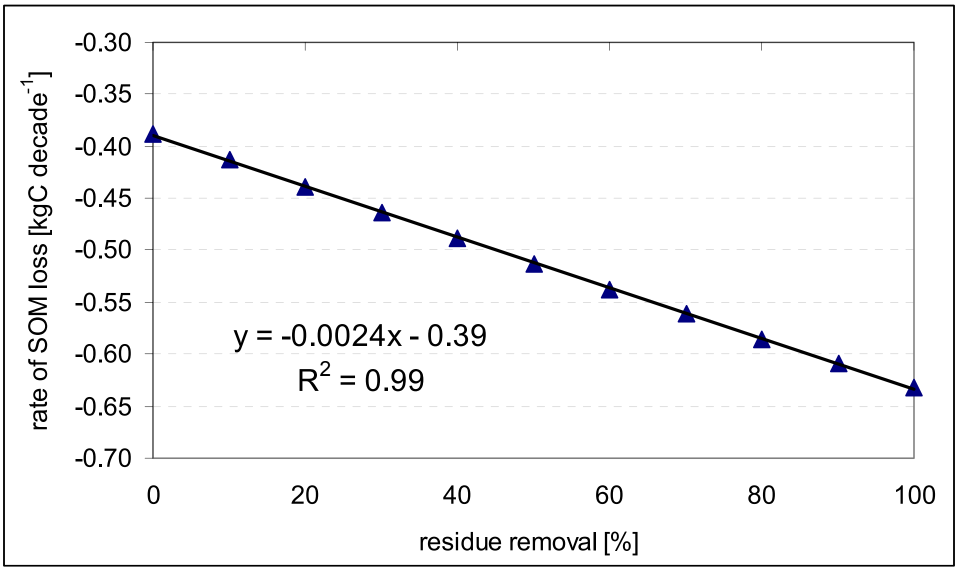

Figure 9. Rate of SOM loss as function of residue removal at the Józsefmajor site. The SOM loss was simulated by Biome-BGCMuSo v4.0.

7. Spatial extension and multimodel framework

Country-scale crop yield and carbon balance simulations were performed by the 4M crop model and by the developed Biome-BGCMuSo biogeochemical model for the 1986-2100 period. The two major crops, winter wheat and maize were studied for Hungary. A multi-model ensemble simulation system was created using the two plant models and ten different climate projections for the future in order to provide a robust evaluation for the future and estimate the uncertainty of the results.

7.1. Simulation design

The meteorological background was provided by the FORESEE database. The target area was Hungary with a 1/6×1/6 degree horizontal resolution grid. In one modelling exercise maize was assumed for all gridpoints for the whole time period, while in the other case winter wheat was simulated (no crop rotation was assumed). Management is also an essential input for the plant models (e.g. planting, fertilizing, harvesting, ploughing). The timing of planting was thoroughly studied within the project, because this procedure initiates the growing period of crops, thus has a major role in their entire lifecycle. Since the date of planting depends on environmental conditions like air temperature and soil conditions, the usage of fixed dates is not reasonable, especially for long term simulations. Therefore, weather- and soil condition-dependent planting date estimation methods where developed and validated for Hungary for maize and winter wheat (Dobor et al., 2016). For the simulations a flexible planting calendar was created based on the FORESEE dataset (air temperature) and 4M pre-simulations (soil water content and soil temperature).

7.2. Model calibration

The 4M and the Biome-BGCMuSo models were calibrated using the GLUE (Generalized Likelihood Uncertainty Estimation) method (Beven and Binley, 1992, 2014; Beven and Freer, 2001). The basis of the method is a Monte Carlo Experiment. First the selected sensitive ecophysiological parameters are randomized together within predefined intervals creating a large number of parameter sets. Then the simulations are executed one by one using the different parameter sets for a period when observations are available. Finally the results of the Monte Carlo Experiment are compared to the observations and a likelihood measure is calculated based on the accuracy of the model outputs (i.e. the model-data misfit; Stedinger et al., 2008; Prihodko et al., 2008). Usually the best 5% of the simulations are taken into account by which the calibrated parameter set is determined. In our case the county-scaled yield observations were used, which are disseminated by the Hungarian Central Statistical Office (http://www.ksh.hu). In case of the 4M model four parameters were calibrated for maize and three for winter wheat. In case of the Biome-BGCMuSo eight parameters were calibrated for maize and ten for wheat. In the latter case the calibration was done for one site, Hegyhátsál, where carbon flux measurements are available, which were also taken into account during the calibration (not just the crop yield, like in case of the 4M). For detasils see Dobor (2016).

7.3. Model validation

The model simulations were validated with county-based yield observations for the whole country and with the eddy covariance measurements from the Hegyhátsál site (see above). The model results for the gridpoints were averaged by counties. The results indicated that the quality of the simulations improved after calibration. 4M explains 62 % of the variability of the observations in case of maize (with a 0.12 t ha^{-1} bias) and 49 % in case of winter wheat (with a 0.06 t ha^{-1} bias). The results of the Biome-BGCMuSo explain 10 % of the observed variability for maize and 50 % for winter wheat. In this case the bias is 0.47 t ha^{-1} for maize and -0.73 t ha^{-1} for winter wheat, respectively. The simulated carbon fluxes were validated for the Hegyhátsál experimental site against the eddy covariance measurement results, where the calibrated model showed improved quality in terms of simulation performance. The relatively small correlations between observations and simulations are partly related to the lack of the information on the area of the planted crops, different crop types and the applied human managements, which could change year by year at Hegyhátsál. In case of the Biome-BGCMuSo also a structural feature of the model could cause low correlation in case of maize, where the phenophase-dependent allocation could be essential, but that feature is not yet implemented in the model.

7.4. Results for crop yield

Fig. 10 shows the spatial average of the maize and winter wheat yields for Hungary as estimated by the 4M model for the 1986-2100 period. For the period 2014-2100 ten projections were created driven by the ten climate model results (grey lines). The multi-climate model average and standard deviation can be seen with black solid and dotted lines, respectively. In this case business-as-usual assumptions were applied regarding to the human management techniques (fertilizer amount, lack of irrigation).

The direction of the projected changes is different for maize and wheat. The 4M model results projected 0.15 t ha^{-1} yield decrease per decade for maize, while for winter wheat an increase of 0.07 t ha^{-1} per decade is expected. The standard deviation caused by the climate projections is 1.7 t ha^{-1} in case of maize, and 0.7 t ha^{-1} in case of winter wheat. The expected changes are significant in both cases (t-test; $p<0.001$).

Fig. 11 shows the results of the Biome-BGCMuSo model. In this case the model projected a yield decrease of 0.06 t ha^{-1} $decade^{-1}$ for maize and an increase of 0.05 t ha^{-1} $decade^{-1}$ for winter wheat (the values refer to the multi-climate model mean). The standard deviation caused by the climate projections is smaller than in cased of the 4M results. It is 1.3 t ha^{-1} in case of maize, and 0.4 t ha^{-1} in case of winter wheat. The expected changes are significant in case of winter wheat ($p<0.001$), but not in case of maize.

The two models are in accordance regarding to the direction of the expected changes (expected increase in case of winter wheat, decrease in case of maize). However, Biome-BGCMuSo projected a smaller, non-significant decrease for maize. Based on both models the sensitivity of the yields to the climate model projections is greater in case of maize.

Based on the multi-climate and multi-plant model average the yield is expected to decrease by 0.43 t ha^{-1} and 0.96 t ha^{-1} in case of maize for the 2021-2050 and for the 2071-2100 period, respectively, comparing to the period 1986-2013. For winter wheat the expected yield increase is 0.20 t ha^{-1} and 0.51 t ha^{-1} in the same order. Additional results are available in the PhD thesis of Laura Dobor, which is another major outcome of the project (Dobor, 2016).

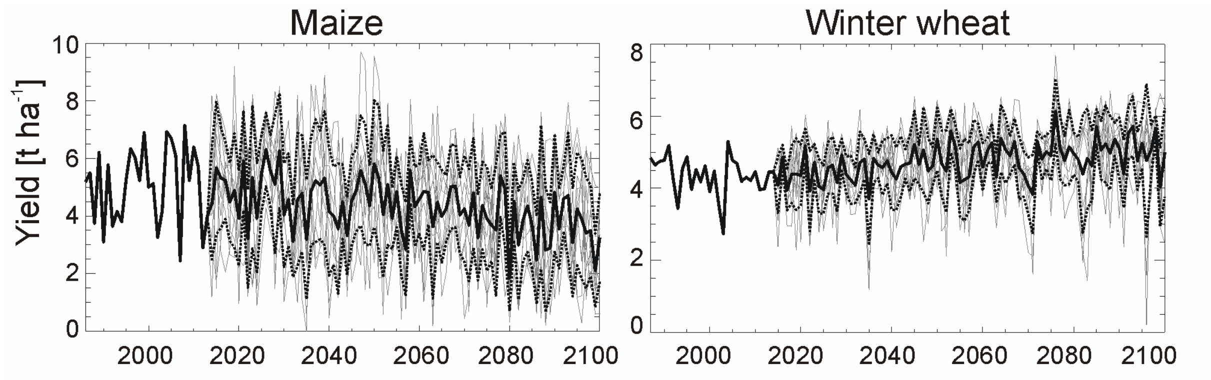

Figure 10. Crop yield simulation results of the 4M model for maize and winter wheat by covering the 1986-2100 period. For the future the ten projections were constructed based on the ten climate model results (grey lines). The black thick line for the future represents the multi-climate model mean, while the dotted lines show the mean plus/minus the standard deviation.

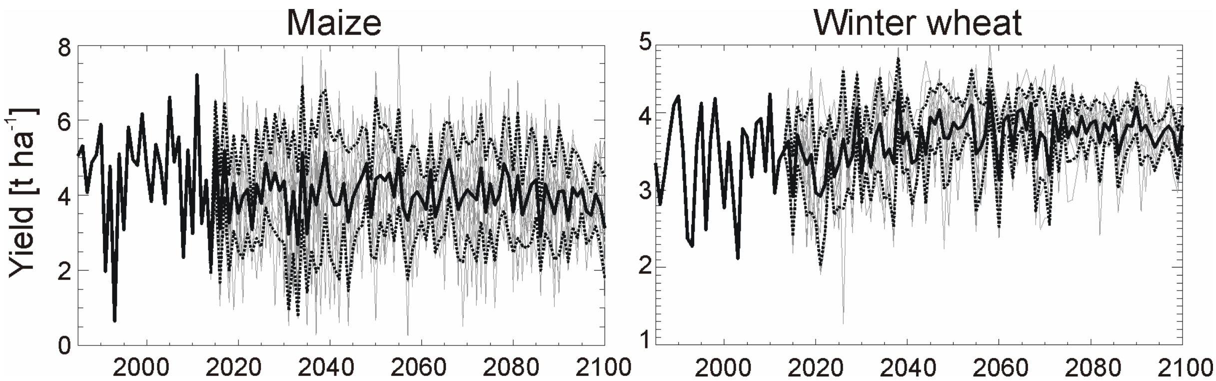

Figure 11. Crop yield simulation results of Biome-BGCMuSo for maize and winter wheat covering the 1986-2100 period. For the future the ten projections are simulated by the ten climate model results (grey lines). The black thick line for the future represents the multi-climate model mean, while the dotted lines show the mean plus/minus the standard deviation.

7.5. Results for carbon balance

Using Biome-BGCMuSo the carbon balance of agroecosystems could also be simulated. In this report only the vertical carbon fluxes are presented (GPP, R_{eco}, and NEE).

Fig. 12 shows maps for the different carbon fluxes in case of maize and winter wheat. The values represent the temporal average of the period 1986-2013 in the past. In case of winter wheat the spatial distribution of the fluxes are strongly driven by the soil texture. In case of maize in addition to the soil properties the effect of annual precipitation sums is also notable. The mean GPP is 953 gC m^{-2} $year^{-1}$ for maize on a country average for 1986-2013, while it is as high as 1187 gC m^{-2} $year^{-1}$ for winter wheat. Mean R_{eco} is 695 gC m^{-2} $year^{-1}$ for maize and 826 gC m^{-2} $year^{-1}$ for winter wheat. Thus the amount of carbon captured in an average year was 258 g on one square meter in case of maize, while this amount was 362 g for winter wheat (considering only the vertical carbon fluxes).

On a county average decrease of GPP and R_{eco} are projected for the future for both crops. The model results projected 15 gC m^{-2} GPP decrease per decade for maize, and 6 gC m^{-2} decrease for winter wheat. R_{eco} is expected to decrease by 14 gC m^{-2} per decade for maize and 6 gC m^{-2} per decade for winter wheat. These changes are relatively small.

In contrast, NEE does not show any significant trend, thus no changes are expected in the amount of carbon taken up from the atmosphere year by year.

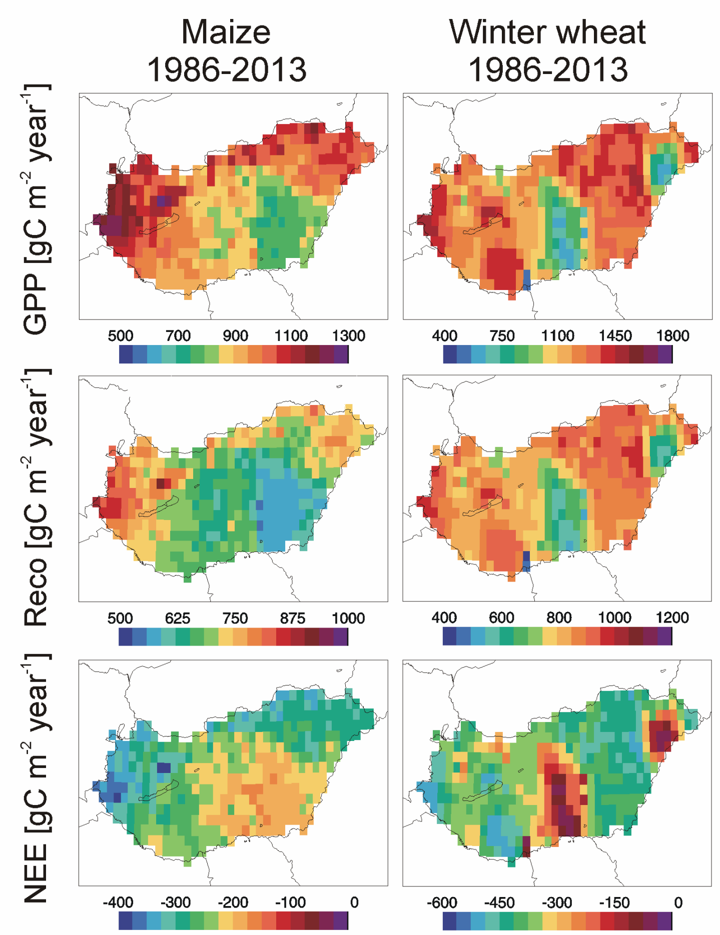

Figure 12. Biome-BGCMuSo simulation results for GPP, R_{eco} and NEE for the period 1986-2013 in case of maize (on the left) and winter wheat (on the right).

7.6. Results for soil water content

Spatial and temporal evolution of soil water content (SWC) was studied for the 2015-2100 period for the whole country assuming 10 climate projections and the two different crops with the Biome-BGCMuSo model. The water content of the soil layers 0-10 cm and 10-30 cm were averaged and the annual means and the summer means were studied separately. Interestingly, the results did not show any significant trend for SWC for the future related to the 1986-2013 period for any crops.

The relationship between the SWC and crop yield was also examined for the future. SWC and yield anomalies were calculated related to the 1986-2013 mean based on the ten climate projections. The multi-climate model mean of the pixel based anomalies were determined and compared to each other. An interesting result is that negative correlation was found between the yield and SWC anomalies for maize, but not from wheat (Fig. 13). This relationship could be explained by the water balance of the plants (i.e. transpiration that depletes SWC). In a year when the environmental conditions are favourable for maize the plant grows more intensively taking up more water from the soil and resulting in a higher yield. In other years when different stress factors limit plant growth the plant does not use that much water, which results in a higher SWC. This finding shows the complexity of the cause-and-effect system, when the low SWC does not necessarily go hand-in-hand with smaller yield, but the higher yield and greater vigour could cause lower SWC through root water uptake. For maize both in the yearly and the summer SWC anomalies showed the same pattern related to the yield, but for winter wheat the results showed no correlation.

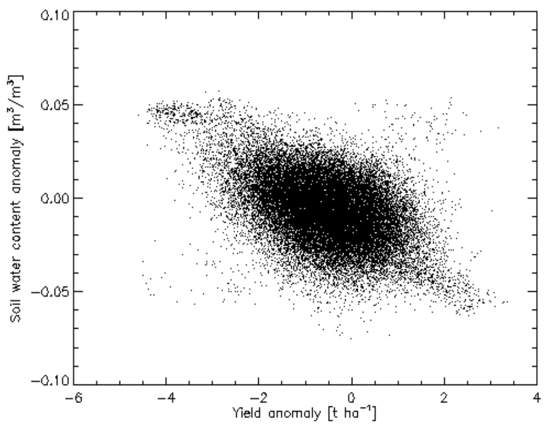

Figure 13. Relationship between the yield and summer soil water content anomalies for the Hungarian gridpoints in case of maize. Every point represents a multi-climate model mean.

8. Conclusions

Soil water depletion and recharge, plant growth, ecosystem carbon balance and soil respiration are closely coupled processes. Soil water content modulates plant growth and gross carbon uptake, which in turn affects evapotranspiration. Evapotranspiration reduces soil water content, thus it directly affects moisture availability. Soil respiration heavily depends on soil temperature and soil moisture and directly affects ecosystem carbon balance. It means that carbon and water balance simulation models are supposed to incorporate soil related processes in detailed and accurate form (Sándor et al., 2016a,b).

Our results demonstrated that none of the models was able to fully capture the daily, seasonal and interannual variability of soil water content and carbon balance components at the sites (and also at other sites; see Sándor et al., 2016a,b). Even HYDRUS-1D, the most promising candidate for physically based soil moisture modeling investigated in the project fails to simulate the effect of plant (stubble) residue cover on soil hydrothermal regime. Developments and model evaluations are strongly recommended in the future to further improve the models' ability to reproduce the measured data.

The major outcome of the project is the construction of Biome-BGCMuSo, which is now a state-of-the-art, globally applicable biogeochemical model, with crop modelling possibility. The model source code, the Windows model executable, sample simulation input files and documentation are freely available at the BBGCMuSo website (http://nimbus.elte.hu/bbgc). The source code is also available at GitHub (https://github.com/bpbond/Biome-BGC/tree/Biome-BGCMuSo_v4.0).

The other major product of the OTKA project is the freely available FORESEE database, which can be used in climate change related impact studies. The FORESEE database is freely available for the scientific community through its website (http://nimbus.elte.hu/FORESEE/) and via the map based query site at http://nimbus.elte.hu/FORESEE/map_query/index.html.

Country-scale simulation results based on FORESEE and Biome-BGCMuSo and 4M provide useful information and support decision makers in adaptation to climate change. The results of the country-scale simulations are available for the public.

Within the OTKA project our emphasized intention was to move towards open and product oriented science. Open and product oriented science means that the outcomes of the project are available to the wider scientific community, without restrictions. The infrastructure (BBGCDB) that supports model application enables transparent, repeatable experiments. We encourage other researchers to follow this logic in other projects.

Publication activity

The selection, collection and post-processing (i.e. bias correction) of climate model results, thus the creation of the FORESEE database, was a major achievement of the project, which enabled the extension of the modeling study for the future. The database creation steps were presented in several forums, firstly in 2012 at the European Geoscience Union Annual Meeting in Vienna, Austria, with a poster (Dobor et al., 2012a) and at the Conference of Doctoral Schools of Environmental Sciences in Budapest (Dobor et al., 2012b) with a lecture. In 2013 a lecture was held at the International Scientific Conference for PhD Students in Győr (Dobor et al., 2013a), where two papers were also published in the conference proceedings (Dobor et al., 2013b; Trombik et al., 2013). During the preparation phase of FORESEE, with the well-defined aim to provide a widely usable database for the end users, a questionnaire was circulated around the climate change related institutes in the target area of the database. The collected results indicated an overall lack of knowledge about the systematic errors of the raw climate model results, and the need of high resolution accessible daily climate data. As FORESEE was constructed following the users' needs, a website was created and the dataset was opened for the scientific community (http://nimbus.elte.hu/FORESEE/). The database was also published at the Zenodo website where a doi was assigned to the FORESEE (10.5281/zenodo.9614). Moreover, a GIS based map query webpage was also created for pixel based download (http://nimbus.elte.hu/FORESEE/map_query/index.html). The creation of the database was published in details in the open access, peer reviewed Geoscience Data Journal (Dobor et al., 2015).

The FORESEE database was used in different studies including peer reviewed papers. Within the OTKA project it was used to estimate the planting dates of maize and winter wheat in the future under different climate scenarios. The results were published in Agricultural and Forest Meteorology (Dobor et al., 2016). Several collaborations were triggered by FORESEE and mainly forest related studies were published, where the project participants were co-authors (Tóth et al., 2013; Hlásny et al., 2014b, 2015; Kern et al., 2015, 2016; Horemans et al., 2016). Among the studies, as part of the research plan, the impacts of climate change on the soil water regime were studied for the Bükk Mountain for arable lands, grasslands and forests (Farkas et al., 2014).

Several test simulations and benchmark runs were performed with both the 4M and the Biome-BGC models, and the results were presented in different conferences. The first crop yield projection results by the 4M model were presented at the 12th European Conference on Applied Climatology in Łodz, Poland, in the form of a poster (Dobor et al., 2012c).

The efficiency of the 4M crop model in simulating the effects of different fertilizer levels was presented in Applied Ecology and Environmental Research (Micskei et al., 2016). Calculated biomass formation results were compared to observed data which were collected in a long-term field experiment. The model successfully simulated the differences between the years, as well as the effects of the different fertilization levels. However, the model underestimated the inter-annual variability of the yield, which is an indicator of a more fundamental problem of crop modeling. The study indicated that at present crop models are unable to handle the effects of environmental (biotic and abiotic) stress factors adequately.

Grassland carbon balance related results with the developed Biome-BGCMuSo model were presented in 2013 at the Open Science Conference: Greenhouse Gas Management in European Land Use Systems in Antwerp, Belgium (Barcza et al., 2013b). Cropland simulations and their comparison with measurements at Józsefmajor and Hegyhátsál were presented at the 4th iLEAPS Science Conference in Nanjing, China (Dobor et al., 2014a).

Biome-BGCMuSo was continuously developed and it is still under development. Within the frame of the OTKA project a website was created and published (http://nimbus.elte.hu/bbgc/), where the model source code and executable are accessible and an up-to-date User's Guide is also available (Hidy et al., 2015). After the latest Biome-BGCMuSo paper, which was published in 2012 (Hidy et al., 2012) a new study was prepared during the project and submitted to the Geoscientific Model Development containing the new developments which describe several modules of the model (Hidy et al., 2016). The paper is still under review at the journal by the time of the submission of this final report. Besides the continuous model developments the original Biome-BGC model is still in use by our team and resulted in a publication in Forest Ecology and Management (Hlásny et al., 2014a).

Our team participated in the BioVeL (Biodiversity Virtual e-Laboratory, http://www.biovel.eu; Hardisty et al., 2016) project, where Biome-BGC was embedded into a web-based virtual laboratory environment (Horváth et al., 2014). The so-called Biome-BGC Projects Database & Management System (BBGCDB) was created to support model application for non-experts. Within BBGCDB pre-processed input data could be stored for the model (http://ecos.okologia.mta.hu/bbgcdb). Different projects could be run on the BioVeL Portal: single model run, complex Monte Carlo experiments, sensitivity analysis and calibration workflows were also implemented. A detailed tutorial was also compiled for beginners describing both the database and the portal where simulations can be initiated (http://nimbus.elte.hu/bbgc/files/BBGCDB_tutorial_first_steps_v03.pdf).

The results of the first sensitivity analysis and calibration with the Biome-BGCMuSo were presented at the Science and Solutions for a Sustainable Environment Conference in Dublin, Ireland in 2014 (Dobor et al., 2014b).

The calibration and validation of the models for maize and winter wheat were presented in a doctoral thesis (Dobor, 2016) together with the expected changes of productivity and carbon balance for the future. Business-as-usual management settings and also alternative scenarios (e.g. irrigation and different fertilization amounts) were tested in order to quantify the sensitivity of the models.

During the OTKA K104816 project our team was invited to participate in the work of the FACCE MACSUR Knowledge Hub (http://macsur.eu). The knowledge hub FACCE MACSUR brings together the excellence of research in modelling grasslands, livestock, crops, farms, and agricultural trade in order to illustrate to political decision makers how climate will affect regional farming systems and food production in Europe. Biome-BGCMuSo was used in the MACSUR grassland model intercomparison project, together with 8 additional, state-of-the-art grassland models (Ma et al., 2014). The results indicated that Biome-BGCMuSo simulates the carbon and water fluxes with acceptable quality, and the quality of the simulations is comparable to the other well known, state-of-the-art models like AnnuGrow, PaSim, SPACSYS, ARMOSA, EPIC, STICS, LPJmL and CARAIB. None of the models were able to simulate soil water content accurately. The results indicate that developments are needed in the soil hydrology submodules to provide reliable estimates, especially in arid and semi-arid regions (Sándor et al., 2015, 2016a,b). This is a major outcome of the project as one of the main aims was to test the applicability of the models to simulate soil water content.

Results of the soil respiration measurements and soil water content monitoring and modeling efforts at Józsefmajor cropland site were published in the form of both a poster and a conference proceeding (Gelybó et al., 2015a,b). According to the published results, HYDRUS-1D is capable of simulating soil water content in different agricultural soils. The short and long term effect of soil tillage (ploughing, cultivator) as a disturbance on soil CO_2 emission was presented at the Plant Biology Congress in Prague, Czech Republic (Dencső et al., 2016) and at the European Geoscience Union Annual Meeting in Vienna, Austria, in the form of a poster (Gelybó et al., 2016). The results were obtained from regular monitoring and campaign measurements after tillage application performed within the frame of the project. Laboratory experiment using soils of different tillage treatments at Józsefmajor was carried out to investigate the relationships between soil water potential and soil CO_2 emission, and the results were published in Agrokémia és Talajtan (Tóth et al., 2014b).

Based on the results of the eddy covariance measurements at Hegyhátsál (that was supported by the OTKA project), a study was published where tall-tower and aircraft measurements were combined in order to estimate the uncertainty of the CO_2 mole fraction within the planetary boundary layer (Haszpra et al., 2015).

Based on a footprint analysis that used eddy covariance measurement results at the Hegyhátsál site, remotely sensed GPP data was assessed against tall tower measurements. Adaptation and validation methods were presented for the MOD17 light use efficiency model for Hegyhátsál located within a heterogeneous cropland and the results were published in Agricultural and Forest Meteorology (Gelybó et al., 2013). As the study showed, the choice of input datasets is important for improving model accuracy; however the calibration and/or structural improvements of the light use efficiency model are essential in the elimination of the poor characterization of the ecosystem. Building on the Hegyhátsál eddy covariance data, another summary paper was published about the carbon dioxide exchange measurements in Hungary in Légkör in Hungarian (Barcza et al., 2013a).

The research activity which was supported by the OTKA K104816 project has not been ended with this final report. Several papers are expected to be published in the following years related to the project results, and further research and follow-up projects are planned based on the current results. Our group has already started to work on a paper, where the model results (Biome-BGCMuSo, 4M, HYDRUS-1D) are validated against eddy covariance, biomass and soil water content measurements carried out both within (Hegyhátsál and Józsefmajor) and outside Hungary (Klingenberg cropland eddy covariance site in Germany, Křesin cropland site in the Czech Republic).

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Appendix I.

Workplan items for project OTKA K104816

September 2012-August 2013

- Compilation of the available measurement data (Józsefmajor, Hegyhátsál).
- Creation of database of measurement results in standardized format.
- Creation of „management history" data for Józsefmajor and Hegyhátsál.
- Documentation of the meteorological and ancillary input requirements of the models.
- Test simulations with the models (HYDRUS-1D SOILCO2, Biome-BGC, ANTHRO-BGC, 4Mx) using existing data
- Initiation of field measurements of soil respiration and ancillary parameters at Józsefmajor based on predefined protocol. Data analysis and data processing.
- Continuous operation and maintenance of the two eddy covariance systems at Hegyhátsál. Processing and quality control of raw eddy covariance data.

September 2013-August 2014

- Evaluation of the accuracy of soil moisture simulations by HYDRUS-1D SOILCO2, Biome-BGC, ANTHRO-BGC and 4Mx at the measurement sites.
- Creation of recommendations for the improvements and possible developments of the models.
- Testing of models in extremely rainy (2010) and extremely dry (2011) weather conditions.
- Evaluation of the accuracy of soil respiration simulations with HYDRUS-1D SOILCO2, Biome-BGC and ANTHRO-BGC
- Simulation of crop yield with 4Mx and ANTHRO-BGC at Józsefmajor and Hegyhátsál.
- Continuation of soil respiration, soil moisture and leaf area index measurements at Józsefmajor (same frequency and replicates as in the previous year).
- Continuous operation and maintenance of the two eddy covariance systems at Hegyhátsál.

September 2014-August 2015

- Implementation of soil disturbance effects (ploughing, minimum tillage) in the hydrology representation of the models.
- Evaluation of the effect of soil physical properties (soil texture) on the simulation results.
- Assessment of possibilities to include country-specific parameters in the models (instead of using pedotransfer functions from the international literature).
- Evaluation of the effects of soil disturbance on the carbon balance related simulation results.
- Implementation of residue management in Biome-BGC and ANTHRO-BGC.
- Assessment of improved soil hydrology representation on the simulated soil respiration and carbon balance.
- Continuation of soil respiration, soil moisture and leaf area index measurements at Józsefmajor (same frequency and replicates as in the previous years).
- Continuous operation and maintenance of the two eddy covariance systems at Hegyhátsál.

September 2015-August 2016

- Evaluation of the effect of different management practices (ploughing, minimum tillage) on the measured soil moisture.
- Evaluation of the management dependent model results, and the effect of moving from one management practice to another.
- Assessment of the long term effect of residue management on the simulated carbon balance at the sites.
- Evaluation of the possibility to increase soil organic carbon content with improved residue management based on simulation results.
- Simulation of Hungary-wide soil moisture and carbon balance with the improved models (primarily with the improved Biome-BGC and ANTHRO-BGC).
- Evaluation of the spatial pattern of simulated soil moisture and carbon balance and the interannual variability of the country-wide simulation results.
- Synthesis of measurements and model developments.