Olga E. Sukhoveeva[1*], Dmitry V. Karelin[1,2]
[1] Institute of Geography, Russian Academy of Sciences, Moscow, Russia
[2] Center for Problems of Ecology and Productivity of Forests, Russian Academy of Sciences, Moscow, Russia
*** Corresponding author:** olgasukhoveeva@gmail.com

APPLICATION OF THE DENITRIFICATION-DECOMPOSITION (DNDC) MODEL TO RETROSPECTIVE ANALYSIS OF THE CARBON CYCLE COMPONENTS IN AGROLANDSCAPES OF THE CENTRAL FOREST ZONE OF EUROPEAN RUSSIA

ABSTRACT. The retrospective dynamics of major components of the carbon cycle under land use changes in the Central Forest zone of European Russia was investigated. This area is known as one of the most important agricultural and economical regions of the country. We applied the process-based simulation model DNDC (DeNitrification-DeComposition) recommended by UNCCC and world widely used. In this study the DNDC model was parameterized for Russian arable soils using official statistical information and data taken from published sources. Three main carbon variables in agrolandscapes were modelled: soil organic carbon, soil respiration, and net ecosystem exchange over the period of 1990-2017. For the analysis six administrative regions were selected: three with unchanged (permanent) arable land structure (Kaluga, Moscow, and Yaroslavl), and other three with changed crop rotation (Kostroma, Smolensk, and Tver). All regions in the study are characterized by homogeneous soil cover and similar cultivated crops. The results of the modelling were verified using the data from field CO_2 fluxes observations in the European part of Russia. In growing season, the agrolandscapes function as a net carbon sink and accumulate C from the atmosphere into plant biomass. The dynamics of organic carbon in soil under growing crops depends on organic fertilizers in cultivation technologies, and if they aren't inputted, soil loses carbon. During the last 30 years the cumulative rates of net ecosystem exchange and soil respiration had decreased mostly due to reduction of arable land area. CO_2 emission and soil organic carbon losses are the most important controls of land degradation. Based on the dynamic patterns of CO_2 fluxes, the regions of the Central Forest zone could be separated into two groups. The group with central location characterized by intensive soil respiration and high rate of accumulation of organic carbon in soil, whereas peripheral group characterized by losses of soil organic carbon and low rates of soil respiration. According to the modelling, within the period of observations the inter-annual changes of carbon fluxes are mainly controlled by rising air temperature and heat supply, variable precipitation, and increasing concentration of CO_2 in the atmosphere. Among human activity the most important are change of arable land area and decreasing amount of fertilizers.

KEY WORDS: Carbon dioxide, Land Degradation Neutrality, Net Ecosystem Exchange, simulation modelling, soil organic carbon, soil respiration

CITATION: Olga E. Sukhoveeva, Dmitry V. Karelin (2019) Application of the DeNitrification-DeComposition (DNDC) model to retrospective analysis of the carbon cycle components in agrolandscapes of the Central Forest zone of European Russia. Geography, Environment, Sustainability,
Vol.12, No 2, p. 213-226
DOI-10.24057/2071-9388-2018-85

INTRODUCTION

Mathematical methods and simulation modelling are widely used in geography and global ecology. Some of these models are focus on the cycles of nitrogen and carbon as the most important biogeochemical elements. They proved to be effective to solve specific agricultural goals such as to forecast and create the programs for reduction of Greenhouse Gases (GHG) fluxes and emissions from soils to the atmosphere under anthropogenic impact, to develop recommendations for proper use of agricultural technologies for sustainable land use, and to decrease losses of yields or soil organic carbon due to unfavorable environmental conditions.

The UN Convention to Combat Desertification considers the dynamics and balance of soil organic content as one of the most important indicators of the recent concept namely Land Degradation Neutrality (LDN), which is in turn a key for achieving LDN target defined in the Sustainable Development Goal 15.3 (UNCCD 2015). The UN Framework Convention on Climate Change (1992-2018) admits that models can be used as an alternative instrument to the IPCC methods for estimation of GHG emission from agriculture if being adapted for different countries and environmental conditions (Estimation of emissions from agriculture 2004; Report of the 38th meeting 2012).

In these documents, among the numerous biogeochemical models for estimation of GHG emission from agriculture, DNDC model (DeNitrification-DeComposition) is declared as the most suitable. It is the only model officially used at national level. Advantages of the model are free access, friendly and simple interface, diurnal format of modelling, taking into account both natural and anthropogenic factors, complex and diverse structure of output fluxes including different components of the carbon and nitrogen cycles.

The model DNDC is successfully applied for different regions and types of land use in 14 countries (Bolan et al. 2004). Impressive results in modelling of GHG emissions were obtained in Asia (Frolking et al. 2004; Pathak et al. 2005; Li et al. 2005), USA (Li 2008), Canada (Yadav and Wang, 2017; Guest et al. 2017), and Australia (Chen et al. 2013). Moreover, this model had been used in several international projects for estimation of organic matter and the nitrogen cycle in arable soils (Giltrap et al. 2010; Leip et al. 2008; Rosenstock et al. 2016). In the last years in Russia some authors used the model for analysis of nitrous oxide emission from soil under vegetables (Buchkina et al. 2007; Balashov et al. 2014) and CO_2 emission from forest and wetland ecosystems (Kurbatova et al. 2009). But it wasn't applied for estimation of CO_2 fluxes in Russian agrolandscapes yet.

In our previous study (Sukhoveeva 2018) internal parameters of the model were parametrized according to Russian arable soils specificities. The database for modelling included meteorological parameters, soil cover, crops characteristics, and features of anthropogenic activity (tillage, fertilization, crops yields etc.) in agrolandscapes. In this research we focused on DNDC simulation modelling of the retrospective dynamics of components of the carbon cycle due to land use changes in European part of Russia.

MATERIALS AND METHODS

DNDC is a process-based computer simulation model of the carbon and nitrogen cycling in agricultural ecosystems (Li et al. 1992). Its block structure consists of three subunits: thermo-hydrological, nitrogen (DeNitrification) and carbon (DeComposition). The model requires a large amount of input data and highly depends on their quality. Its parameters are climatic variables (daily maximum and minimum air temperatures and precipitations), soil characteristics (soil texture, pH, bulk density, soil organic carbon, C/N ratio, litter/humads/humus), and agricultural variables (days of sowing and harvesting, yields, biomass production, biomass fractions, C/N ratio in biomass, data and method of tiling, data and amount of fertilizers, data of manure amendment and content of C and N in it). Besides it uses many assumptions on the controls of GHG emissions per soil type.

The Central Forest zone is one the most valuable agricultural and economical areas of European Russia (Fig. 1). It includes 12 administrative units: Bryansk, Ivanovo, Kaluga, Kostroma, Moscow, Orel, Ryazan, Smolensk, Tver, Tula, Vladimir, Yaroslavl regions, and Moscow-city. Sod-podzolic soils are spread most widely in these regions. According to Köppen's classification, climate in these regions is the warm summer variant of the humid continental climate (Chen and Chen 2013), temperate climate according to Alisov's classification.

Three main characteristics of the carbon budget in agrolandscapes were modelled:
- soil organic carbon dynamics as difference between initial and final soil organic carbon content per year,
- soil respiration consisting of root and microbial fluxes,
- Net Ecosystem Exchange (NEE) – difference between Gross Primary Production (i.e. photosynthesis) and Ecosystem Respiration (i.e. sum of aboveground plant respiration and soil respiration).

Taking into account soil type and growing crops in different administrative units, we distinguished 20 agrolandscapes (Table 1). Totally we run 560 modelling experiments over the period of 1990-2017 (28 years). Finally, 3920 values of the carbon cycle components had been used, when creating maps.

At the preliminary stage of modelling we created a database on agroclimatic re-

Fig. 1. Administrative units (in green) of the Central Forest zone of Russia

Table 1. Matrix of CO_2 fluxes modelling in the Central Forest zone of European Russia

Soil type	Crops / Regions	Winter wheat	Winter rye	Barley	Oat	Potato	Structure of arable lands
Sod-podzolics, mainly rather shallow podzolics, Umbric Albeluvisols Abruptic	Kostroma	–	–	+	+	–	Changed
	Yaroslavl	–	–	+	+	+	Unchanged
Sod-podzolics, mainly shallow and non-deep podzolics, Umbric Albeluvisols Abruptic	Moscow	+	–	+	–	+	
	Kaluga	+	–	+	+	+	
	Smolensk	–	+	+	+	–	Changed
	Tver	–	–	+	+	–	

courses of the Central Forest zone. Weather data were provided by Russian Institute of Hydro-Meteorological Information – World Data Center (http://meteo.ru/data) from 16 weather stations. Soil cover characteristics were defined through the Unified State Register of Soil Resources of Russia (2014). Only prevalent soil types covered more than 30% of regions territory were included into the analysis.

Degree-days required for a crop to reach maturity and water demand for cultivated in European Russia varieties were corrected with use of open access sources. Due to the lack of information on particular dates of sowing, harvesting, plowing, input of fertilizers, and other cultivation operations, the average dates and periods for agricultural techniques, recommended by Ministry of agriculture were inputted into the model.

List of growing crops and its yields were summarized from information of Federal State Statistical Service (https://fedstat.ru/). Data on crop fertilizing was obtained from Statistics bulletin "Application of fertilizers for the harvest and works for chemical land melioration" over the period 1990-2017.

Due to the information available, the duration of the analyzed period was 28 years. For better comparison this period was separated into four 7-years intervals, which correspond with the main social and economic changes in the country.

In our study, the structure of arable land and crop rotations were assumed to stay unchanged if they meet the following requirements:

- List of growing crops hadn't been changed during the period 1990-2017,
- Each crop covered more than 5% of territory.

RESULTS

At the preliminary stage of the analysis, six administrative regions in the Central Forest zone of European Russia were chosen: Kaluga, Kostroma, Moscow, Smolensk, Tver, and Yaroslavl regions. They are characterized by homogeneous soil type and the same growing crops. Open access to weather data was also critical in that choice.

The most common soil type in the zone is sod-podzolic – Umbric Albeluvisols Abruptic (WRB 2006), Eutric Podzoluvisols (FAO 1988): sod-podzolic, mainly shallow and non-deep podzolics, and sod-podzolics, mainly rather shallow podzolics. These soil types cover more than 30% of territory in corresponding regions (Table 1).

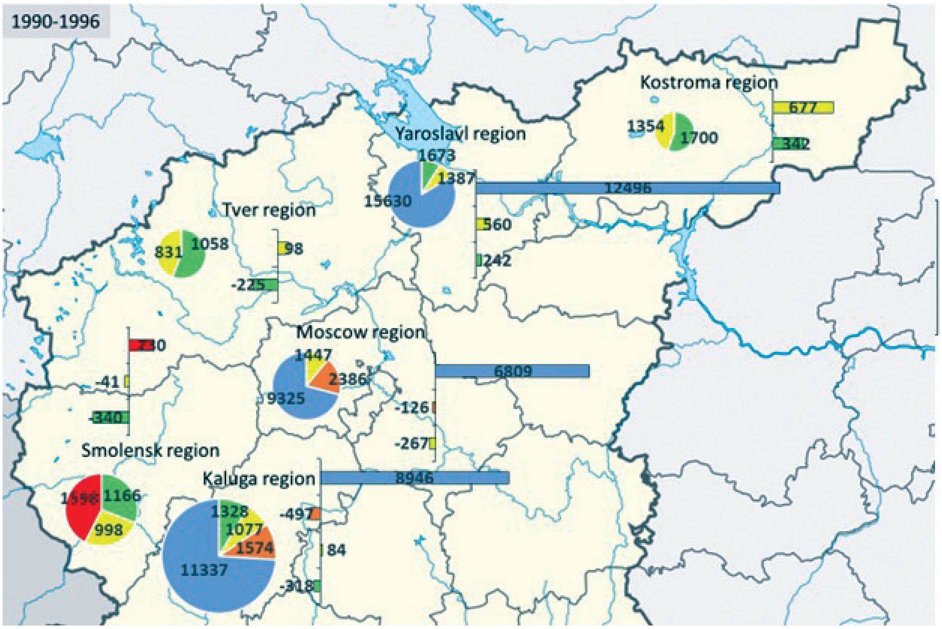
It was also found that the most important crops cultivated in all regions in the study are spring grain crops: barley and oat, as well as potato. Besides, in the southern part of the Central Forest zone predominate winter grain crops such as wheat and rye. In Kaluga, Moscow, and Yaroslavl regions arable land structure is rather stable, with no changes in the list of grown crops during the last 28 years. In contrast, in Kostroma, Smolensk, and Tver regions, areas of each crop vary significantly.

Other regions of the Central Forest zone were excluded from the analysis either due to excessively non-homogeneous soil cover (Bryansk, Ryazan, Tula regions), or the lack of open access meteorological data (Vladimir, Ivanovo, Orel regions).
It is usual that existing official information includes some omissions and uncertainness:
• Official statistical data is averaged on a base of administrative units,
• Boundaries and areas of soil types do not match the administrative division,
• It is not known what soil types are tillaged,
• It is not clear what territories and soil types are occupied by each crop,
• Crop rotations, i.e. spatial and temporal replacement of crops, are unknown,
• Varieties of crops and their requirements to environmental conditions are unknown,
• Arable land area and crops areas are changed.

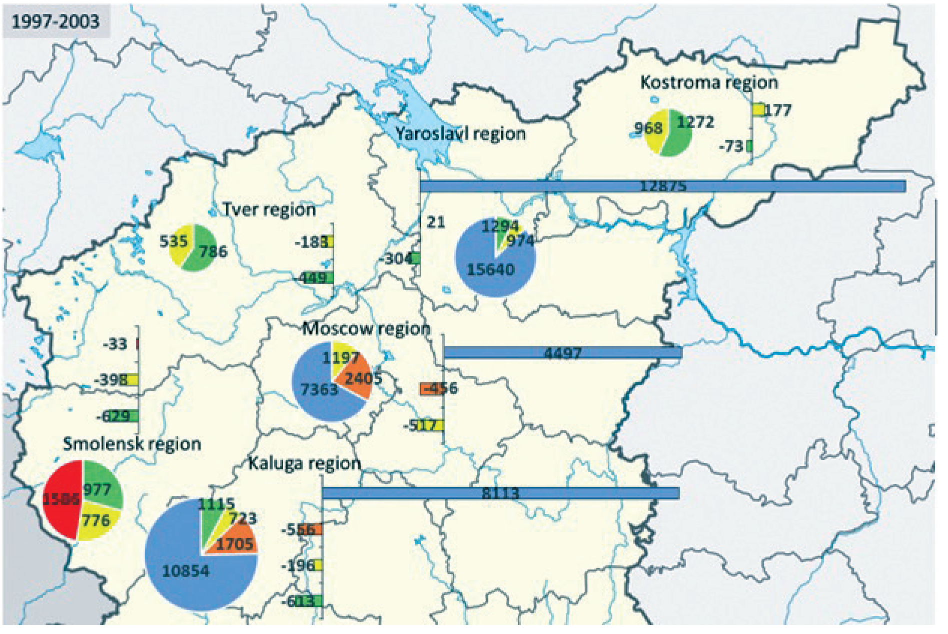
In this study the soil organic carbon dynamics depends on features of growing crops and input of fertilizers. In the northern regions as Kostroma and Tver, such spring grain crops as barley and oat are dominated (Fig. 2), and the losses of organic carbon from soil are typical due to absence of organic fertilizers in cropping technologies (Fig. 3). But for the last 10-15 years the intensity of agriculture, crops yields, and amount of fertilizers had greatly increased, resulting in less carbon losses.

Similarly, according to the modelling the observed dynamics of CO_2 fluxes depends on input of fertilizers, yield changes, and rise of CO_2 concentration in the atmosphere.

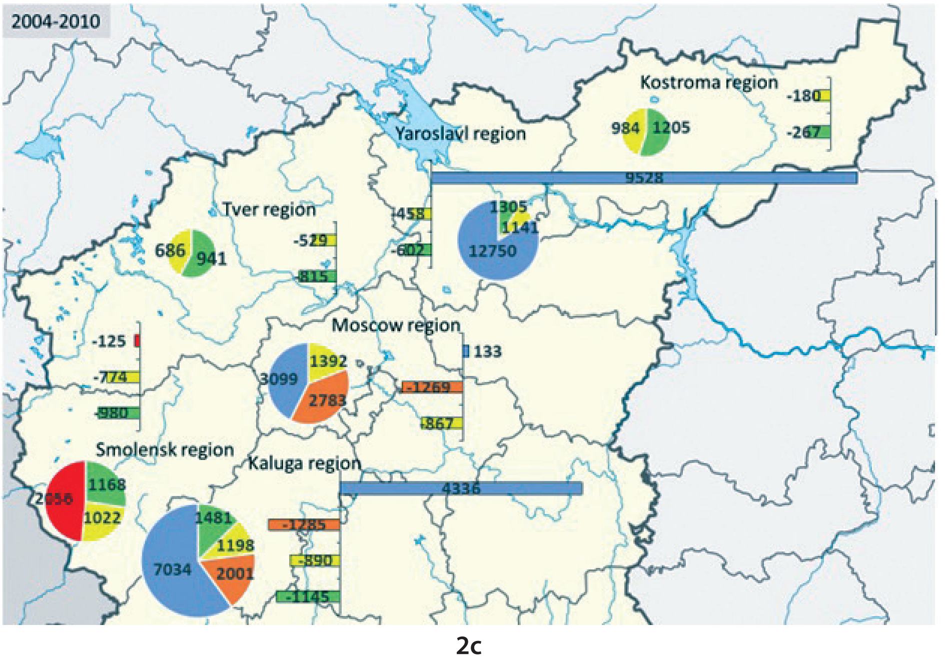
Kostroma, Smolensk, and Tver regions are characterized by decrease of soil respiration in 1990s and following increase in 2010s (Fig. 4). Curiously, it was found that in Tver region the rates of soil respiration were less than 1.0 t C ha^{-1} yr^{-1} during the 28-years period of modelling. This is mostly due to low intensity of agricultural technologies, i.e. small amounts of inputting fertilizers, little plant biomass, and low temperatures as compared to other regions in the study. And vice versa, in Moscow, Kaluga, and Yaroslavl regions,



2a


1997-2003
Kostroma region
968
1272
177
-73
Yaroslavl region
12875
Tver region
535
786
-183
449
21
-304
1294
974
15640
Moscow region
4497
-33
-398
-629
1197
2405
7363
-456
-517
Smolensk region
Kaluga region
1586
977
776
8113
1115
723
1705
10854
-556
-196
-613

2b


2004-2010
Kostroma region
-180
984
1205
-267
Yaroslavl region
9528
Tver region
-458
1305
686
941
-529
-602
1141
815
12750
Moscow region
-125
133
1392
3099
-774
-1269
2783
-980
-867
Smolensk region
Kaluga region
1168
2056
4336
1022
1481
-1285
1198
7034
-890
2001
-1145

2c

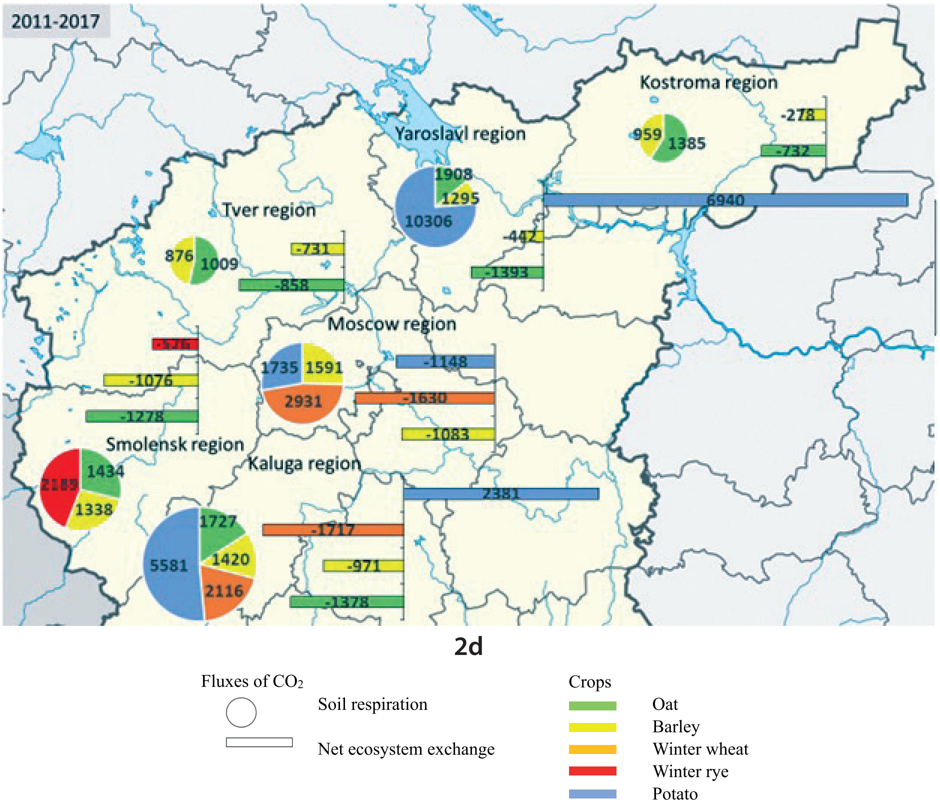


Fig. 2. Annual values of CO_2 fluxes in agrolandscapes of the European Russia by crops and regions by 7-years intervals, kg C ha^{-1} yr^{-1}

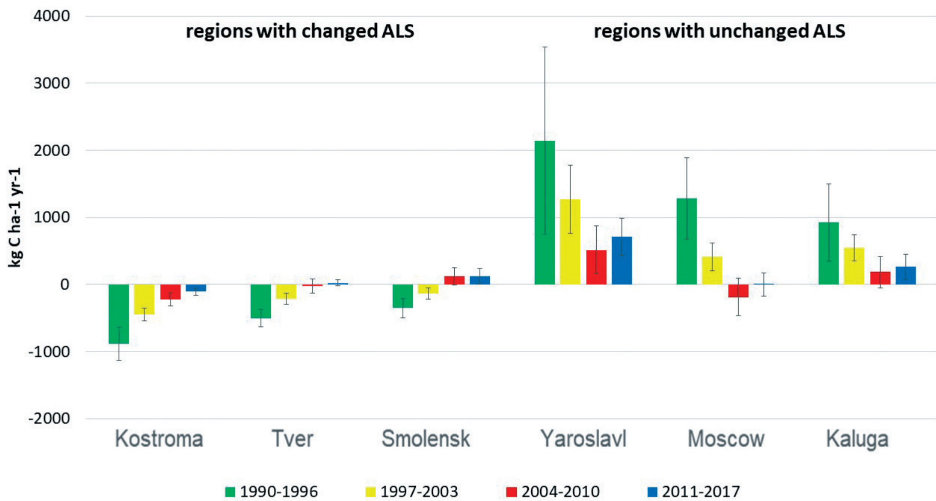


Fig. 3. Spatiotemporal mean annual dynamics of soil organic carbon in agrolandscapes of the studied regions of European Russia by 7-years intervals. Here and on other figures: ALS – arable land structure, means with standard deviations are given

highly productive crops such as winter wheat and potato are grown (Fig. 2). They are characterized by use of great amount of fertilizers in cropping technologies, resulting in general accumulation of carbon in soils. But in the last decades in these regions carbon deposition and rate of soil respiration were reducing due to decrease of fertilizers input.

Cumulative soil respiration decreased due to reduction of arable soil area in these regions in general (Fig. 5). Its mean rates were equal to 800-1400 kt C ha^{-1} yr^{-1} in 1990-1996 and 200-300 kt C ha^{-1} yr^{-1} in 2011-2017.

And during the observed period the carbon balance in agroecosystems was changed between the net source of CO_2 to the atmosphere and sequestration (Fig. 6). Thus, ecosystems of the zone in 1990-2003 acted as the net source of carbon (400-800 kt C ha^{-1} yr^{-1}), whereas in 2004-2017 NEE firstly became close to zero and then the ecosystems were a carbon sink during vegetative period (Fig. 7).

Finally, based upon the direction and intensity of CO_2 fluxes, geographical location, and the degree of anthropogenic impact, the agrolandscapes of the Central Forest zone of European Russia could be separated into two large administrative groups:

- "Central" – Moscow, Kaluga, Yaroslavl regions – intensive agriculture (including winter wheat and potato cropping), stable structure of arable land and agricultural production, prevailing accumulation of organic carbon in soil (0-2.0 t C ha^{-1} yr^{-1}), high rate of soil respiration (2.0-6.0 t C ha^{-1} yr^{-1});
- "Peripheral" – Kostroma, Smolensk, and Tver regions – small number of crops, extensive agriculture, losses of soil organic carbon (0-0.9 t C ha^{-1} yr^{-1}), low rate of soil respiration (< 2 t C ha^{-1} yr^{-1}).

DISCUSSION

In our previous study it had been proved that the parametrized DNDC model is rather effective to estimate components of the carbon cycle in European part of Russia (Sukhoveeva 2018). For verification of the adapted DNDC model to Russian conditions, the data from two field sites were used. Namely seasonal and annual CO_2 emissions were estimated in Kursk and Moscow regions. The results of ANOVA showed that the mean measured and calculated values of emissions were not significantly different (calculated F-criteria were less than critical F-criteria).

Medium positive correlation was also found between the observed and modelled CO_2 fluxes. Thus, in Kursk region the Pearson coefficients correlations between measured and modelled values of soil res-

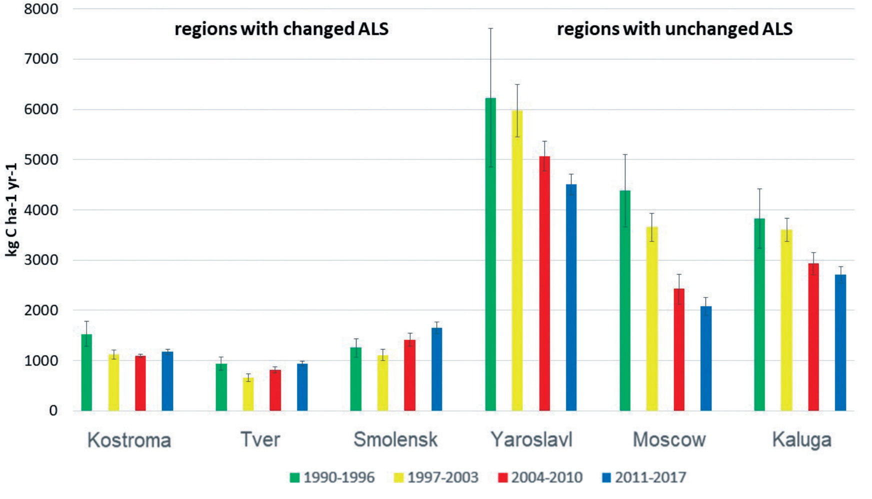


Fig. 4. Spatiotemporal annual dynamics of soil respiration in agrolandscapes of the studied regions of European Russia by 7-years intervals

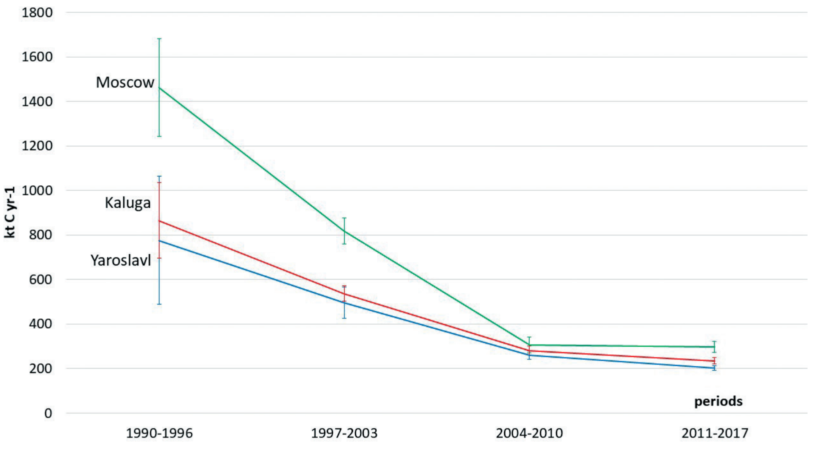


Fig. 5. Modelled cumulative annual rates of soil respiration in the regions haracterized by unchanged arable land structure by 7-years intervals

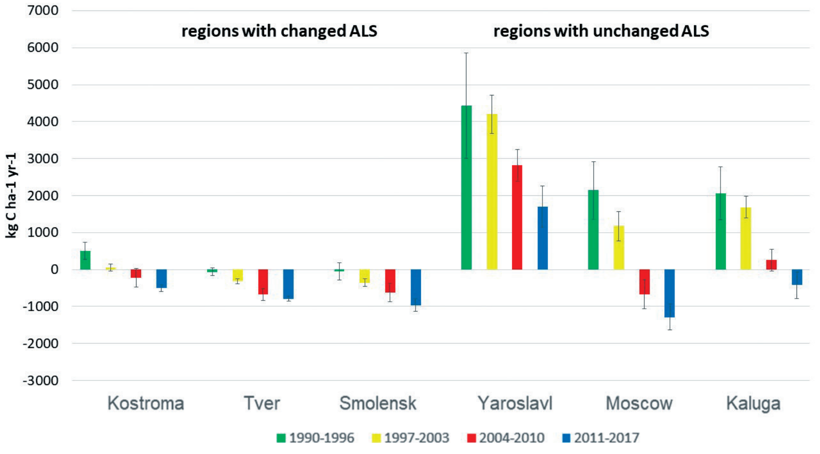


Fig. 6. Spatiotemporal mean annual dynamics of Net Ecosystem Exchange in agrolandscapes of the studied regions of the European Russia by 7-years intervals

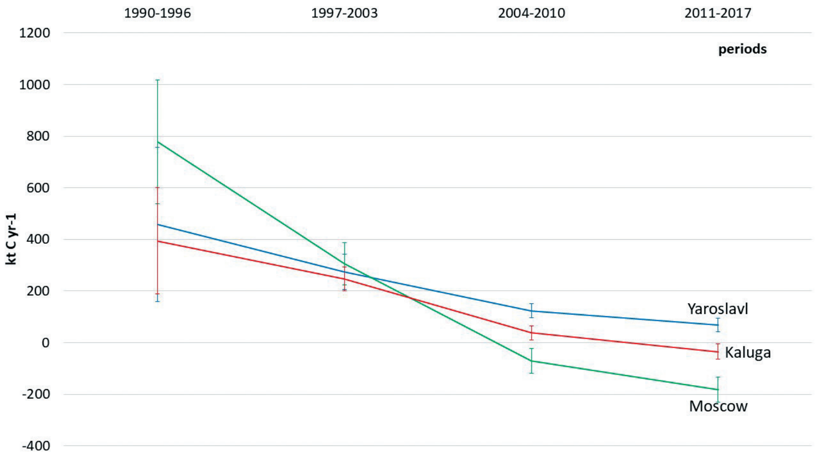


Fig. 7. Modelled cumulative values of Net Ecosystem Exchange in the regions characterized by unchanged arable land structure by 7-years intervals

piration were equal to $r_p = 0.662$, $P = 0.005$ for sunflower, $r_p = 0.533$, $P = 0.028$ for barley, $r_p = 0.531$, $P = 0.028$ for winter wheat, and $r_p = 0.300$, $P = 0.259$ for potato, respectively. In Moscow region the correlation between field measured and modelled values of soil respiration was equal to $r_p = 0.582$, $P < 0.001$ for cereal-fallow crop rotation ($r_p = 0.546$, $P < 0.001$ for winter wheat and $r_p = 0.723$, $P < 0.001$ for fallow, respectively) (Sukhoveeva 2018).

Besides verification of the model was performed by published information on CO_2 emission and carbon balance in arable soils in Moscow, Orel, and Vladimir regions (Table 2). In all cases the measured annual values were inside the interval of predicted by the model ones. Also, the ratios between major CO_2 fluxes were checked with winter wheat taken as example. Modelled ratio of respiration to photosynthesis (0.34-0.36) was similar to ratio in laboratory experiment (0.35-0.60) (Gifford, 1995). The modelled and measured relative inputs of root and microbial respiration were also corresponding to each other (0,33 : 0,67 by the model and 0,34-0,38 : 0,62-0,66 by the field experiment) (Kurganova, 2010). There aren't field experiments for measuring NEE in Russia that's why this CO_2 flux hadn't been used for verification of the model.

Generally arable soils are losing organic carbon and, in this study, anthropogenic impact was also found to be the most important for soil C exchange. This conclusion has been confirmed widely (Kolchugina et al. 1995; Lal 2004; Semenov et al. 2008; Larionova et al. 2010; Kosolapov et al. 2015).

Table2. Verification of the model DNDC in the Central Forest zone of European Russia on the base of published results of field measurements

Parameters	Annual C balance in soil, kg C ha^{-1} yr^{-1}			Annual CO_2 emission from soil, kg C ha^{-1} yr^{-1}					
Model values	162,6-277,7	-248… - 55 Without fertilizers	+4988- +6111 With fertilizers	2258-3664	7420-8196	701-2540	6658-7709	427-800 Without fertilizers	1307–4074 With fertilizers
Field values	250	-1004	+6016	3304	7850	788-3066	3767-9899	1753	3019
Crops	Crop rotation winter wheat – fallow	Potato		Crop rotation winter wheat – fallow	Winter wheat	Fallow	Barley	Potato	
Region	Pushchino, experiment of Institute of physical-chemical and biological problems of soil science RAS	Vladimir, Long-term experiment of Institute of organic fertilizer and peat		Pushchino, experiment of Institute of physical-chemical and biological problems of soil science RAS	Orel, western part	Moscow, Long-term experiment of Timiriazev academy		Vladimir, Long-term experiment of Institute of organic fertilizer and peat	
Period, yr	2000-2004	2004-2014		2000-2004	2013	2005-2008		2004-2014	
References	Sapronov, 2008	Lukin, 2015		Sapronov, 2008	Karelin et al., 2017	Chistotin and Safonov, 2016		Lukin, 2015	

In all studied regions the dynamics of soil organic carbon storage in agrolandscapes was negative, especially under annual crops. Therefore, both emissions and carbon net accumulation rates in soil were decreased. Similar observations were made by Fedorov (2017); in his research broad-scale changes in land use (substitution of arable lands by grasslands and pastures) followed by declining fertilizers input, resulted in decrease of both CO_2 soil emission and net carbon accumulation from the atmosphere. Moreover, source pattern of net ecosystem exchange resulted from soil organic carbon losses and further degradation of agroecosystems (Kirschbaum and Mueller 2001).

Variability of modelled estimates could be evaluated by standard deviation or coefficient of variation.

The smallest standard deviations were found for Tver region < 100 kg C m^{-2} yr^{-1}. This is correct for barley and oat cultivated in this region, and for all carbon fluxes taken into account: soil respiration, soil organic carbon, and net ecosystem exchange. The biggest standard deviations were obtained for potato > 1000 kg C m^{-2} yr^{-1} also for three major CO_2 fluxes in the regions characterized by unchanged arable lands structure (Kaluga, Moscow, Yaroslavl).

The smallest coefficients of variation (less than 8%) were found for soil organic carbon and NEE in the agrolandscapes of Yaroslavl and Kostroma regions, where barley and oat are cultivated. Whereas the greatest coefficients of variation (more than 150%) are characteristic for soil organic carbon under grain crops in Moscow and Kaluga regions.

Two the most probable factors influencing instability of the carbon cycle components are climate change, including temperature increase, and further rise of CO_2 concentration in the atmosphere at the rate of 3 ppm per year, according to WMO message (WMO 2017). Thus, during the last four decades, under the most expressed climate changes due to Global Warming events, the strong increase in heat supply in the Central Forest zone was observed (Sukhoveeva 2016). During that period both mean annual (+0.3 °C/10 yr) and mean monthly (+0.9 °C/10 yr) air temperatures were rising. This was also true for the trends of positive degree-days (+48 °C/10 yr) and longevity of vegetative periods. Sum of precipitation (monthly trend 5 mm/10 yr, annual trend 30 mm/10 yr) and moisture supply in vegetative period enhanced, too, but they became unstable.

Hopefully the results of this study will provide help to create recommendations (i) to decrease losses of yields due to unfavorable environmental conditions, (ii) to reduce GHG emissions from arable soils to the atmosphere due to land use practices, and (iii) to promote carbon sequestration through sustainable land management practices targeting on the LDN achievement (Sanz et al. 2017).

CONCLUSIONS

The DNDC model has been successfully applied for simulation of the carbon cycle components in agrolandscapes of the Central Forest zone in European Russia. The dynamics of soil respiration, net ecosystem exchange, and soil organic carbon content in arable lands were estimated over the 28-yr period (1990-2017) to evaluate how carbon fluxes and stocks depend on geographical location and administrative belonging. Spatial and temporal variations of CO_2 fluxes were plotted and mapped for arable soils in administrative regions characterized by homogeneous soil type and the same growing crops. According to the results of the study, the regions of the Central Forest zone of European Russia were separated into two groups. Central regions are characterized by intensive soil respiration and accumulation of organic carbon in soil, whereas peripheral ones are characterized by losses of soil organic carbon and low rates of soil respiration. At present the agrolandscapes of the Central Forest zone during vegetative season are functioning as carbon sinks and accumulate carbon from the atmosphere into plant biomass. In soil under growing crops organic carbon is absorbing, if organic fertilizers are present in cultivate technologies, but under technologies without organic fertilizers, soil loses carbon. In Moscow, Kaluga, and Yaroslavl regions characterized by unchanged crop rotations, both rate of cumulative soil respiration and net ecosystem exchange are decreasing due to reduction of arable land area during the last 28 years.

ACKNOWLEDGEMENTS

Modelling dynamics of soil organic carbon, soil respiration, and net ecosystem exchange was performed for the Project of Russian Science Foundation № 18-17-00178; agroclimatic recourses and local climate change in the Central Forest zone were evaluated for Fundamental scientific research theme № 0148-2018-0006 (renewed № 0148-2019-0009) and Program of Presidium of RAS № 51 (№ 0148-2018-0036)

REFERENCES

Balashov E., Buchkina N., Rizhiya E., and Farkas C.S. (2014). Field validation of DNDC and SWAP models for temperature and water content of loamy and sandy loam spodosols. International agrophysics, 28 (2), pp. 133-142.

Bolan N.S., Saggar S., Luo J., Bhandral R., and Singh J. (2004). Gaseous emissions of nitrogen from grazed pastures: processes, measurements and modeling, environmental implications, and mitigation. Advances in agronomy, 84, pp. 38-120.

Buchkina N.P., Balashov E.V., Rizhiya E.Y., and Li C. (2007). Application of DNDC model for Russian agro-ecosystems. In: Denitrification: a challenge for pure and applied science. Book of abstracts. University of Aberdeen, pp. 17.

Chen C., Chen D., Pan J., and Lam S.K. (2013). Application of the denitrification-decomposition model to predict carbon dioxide emissions under alternative straw retention methods. Scientific World Journal, 25, pp. 851-901. DOI: 10.1155/2013/851901.

Chen D. and Chen H.W. (2013). Using the Köppen classification to quantify climate variation and change: an example for 1901-2010. Environmental Development, 6, pp. 69-79.

Chistotin M.V. and Safonov A.F. (2016). Temporal patterns of respiration of an agro-sod-podzolic soil as controlled by organic matter content and meteorological factors. Problemy agrokhimii i ekologii, 3, pp. 52-58. (in Russian)

Estimation of emissions from agriculture. (2004). United Nations framework convention on climate change. FCCC/SBSTA/2004/INF.4. GE.04–61454. – Bonn: UNFCCC, 28 May 2004. Available at: http://unfccc.int/resource/docs/2004/sbsta/inf04.pdf. [Accessed 1 Dec. 2018].

FAO-Unesc. (1988). Soil Map of the World. Revised Legend. World Resources Report, 60. Rome: FAO.

Fedorov B.G. (2017). Russian carbon balance. Moscow: Scientific consultant (in Russian).

Frolking S., Li C., Braswell R., and Fuglestvedt J. (2004). Short- and long-term greenhouse gas and radiative forcing impacts of changing water management in Asian rice paddies. Global Change Biology, 10 (7), pp. 1180-1196.

Gifford R.M. (1995). Whole plant respiration and photosynthesis of wheat under increased CO2 concentration and temperature: long-term vs. short-term distinctions for modelling. Global Change Biology, 1, pp. 385-396.

Giltrap D.L., Li C., and Saggar S. (2010). DNDC: a process-based model of greenhouse gas fluxes from agricultural soils. Agriculture, Ecosystems & Environment, 136 (3-4), pp. 292-300.

Guest G., Kröbel R., Grant B., Smith W., Sansoulet J., Pattey E., Desjardins R., Jégo G., Tremblay N., and Tremblay G. (2017). Model comparison of soil processes in eastern Canada using DayCent, DNDC and STICS. Nutrient Cycling in Agroecosystems, 109 (3), pp. 211–232.

Karelin D.V., Goryachkin S.V., Kudikov A.V., Lunin V.N., Dolgikh A.V., Lyuri D.I., and Lopes de Gerenu V.O. (2017). Changes in carbon pool and CO2 emission in the course of postagrogenic succession on gray soils (Luvic Phaeozems) in European Russia. Eurasian Soil Science, 50 (5), pp. 559-572. DOI: 10.7868/80032180X17050070

Kirschbaum M.U.F. and Mueller R. (2001). Net Ecosystem Exchange. – Australia: Cooperative Research Centre for Greenhouse Accounting.

Kolchugina T.P., Vinson T.S., Gaston G.G., Rozhkov V.A., and Schlentner S.F. (1995). Carbon pools, fluxes, and sequestration potential in soil of the Former Soviet Union. In: R. Lal, J. Kimble, E. Levine, B.A. Stewart, ed., Soil Management and greenhouse effect. Boca Raton, London, Tokyo: Lewis Publishers, pp. 25-40.

Kosolapov V.M., Trofimov I.A., Trofimova L.S., and Yakovleva E.P. (2015). Agrolandscapes of Central Cernozem area. Zoning and management. Moscow: Nauka (in Russian).

Kurbatova J. Li C. Varlagin A. Xiao X., and Vygodskaya N. (2008). Modeling carbon dynamics in two adjacent spruce forests with different soil conditions in Russia. Biogeosciences, 5, pp. 969-980.

Kurganova I.N. (2010). Emission and balance of carbon dioxide in terrestrial ecosystems of Russia: doctor thesis. Pushchino: IFXiBPP RAN. (in Russian)

Lal R. (2004). Soil carbon sequestration to mitigate climate change. Geoderma, 123 (1-2), pp. 1-22. DOI: 10.1016/j.geoderma.2004.01.032.

Larionova A.A., Kurganova I.N., De Gerenyu V.O.L., Zolotareva B.N., Yevdokimov I.V., and Kudeyarov V.N. (2010). Carbon dioxide emission from agrogrey soils under climate change. Eurasian soil science, 43 (2), pp. 168-176. DOI: 10.1134/S1064229310020067 (in Russian)

Leip A., Marci G., Koeble R., Kempen M., Britz W., and Li C. (2008). Linking an economic model for European agriculture with a mechanistic model to estimate nitrogen and carbon losses from arable soils in Europe. Biogeosciences, 5, pp. 73-94.

Li C., Frolking S., and Frolking T.A. (1992). A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. Journal of geophysical research, 97 (D9), pp. 9759-9776.

Li C., Frolking S., Xiao X., Moore III B., Boles S., Qiu J., Huang Y., Salas W., and Sass R. (2005). Modeling impacts of farming management alternatives on CO_2, CH_4, and N_2O emissions: A case study for water management of rice agriculture of China. Global Biogeochemical Cycles, 19 (3), GB3010. DOI: 10.1029/2004GB002341.

Li C. (2008). Modeling soil organic carbon sequestration potential with modeling approach. In: Simulation of Soil Organic Carbon Storage and Changes in Agricultural Cropland in China and Its Impact on Food Security. China Meteorological Press.

Lukin S.M. (2015). Carbon dioxide emission in potato agrocenosis on sod-podzolic sandy soils. Vladimirskii zemledelets, 3-4 (74), pp. 22-23. (in Russian)

Pathak H., Li C., and Wassmann R. (2005). Greenhouse gas emissions from India rice fields: calibration and upscaling using the DNDC model. Biogeosciences, 2 (2), pp. 113-123.

Report of the thirty-eighth meeting of the small-scale working group (2012). Bonn: CDM SSC WG.

Rosenstock T.S., Rufino M.C., Butterbach-Bahl K., Wollenberg E., and Richards M. (2016). Methods for measuring greenhouse gas balances and evaluating mitigation options in smallholder agriculture. USA: Springer.

Sanz M.J., de Vente J., Chotte J.-L., Bernoux M., Kust G., Ruiz I., Almagro M., Alloza J.-A., Vallejo R., Castillo V., Hebel A., and Akhtar-Schuster M. (2017). Sustainable Land Management contribution to successful land-based climate change adaptation and mitigation. In: A Report of the Science-Policy Interface. Bonn: UNCCD.

Sapronov D.V. (2008). Long-term dynamics of CO_2 emission from grey forest and sod-podzolic soils: PhD thesis. Pushchino: IFHiBPP RAN. (in Russian)

Semenov V.M., Ivannikova L.A., Kuznetsova T.V., Semenova N.A., and Tulina A.S. (2008). Mineralization of organic matter and the carbon sequestration capacity of zonal soils. Eurasian soil science, 41 (7), pp. 717-730. DOI: 10.1134/S1064229308070065 (in Russian)

Sukhoveeva O.E. (2016). Changes of climatic conditions and agroclimatic recourses in Central Non-Cernozem zone. Proceedings of Voronezh State University. Series: Geography. Geoecology, 4, pp. 41-49. (in Russian)

Sukhoveeva O.E. (2018). Evaluation of spatiotemporal variability of CO_2 fluxes in agrolandscapes of European Russia on the base of simulation modelling: PhD thesis. Moscow: Institute of Geography RAS. (in Russian)

UNCCD. (2015). Science policy brief, 1.

Unified state register of soil recourses of Russia. Versa 1.0. (2014). Moscow: Soils institute.

WMO. (2017). Greenhouse Gas Bulletin, 13.

World reference base for soil resources. (2006). IUSS Working Group. World Soil Resources Reports, 103. Rome: FAO.

Yadav D. and Wang J. (2017). Modelling carbon dioxide emissions from agricultural soils in Canada. Environmental Pollution, 230, pp. 1040-1049. DOI: 10.1016/j.envpol.2017.07.066.

Received on Dec 31st 2018 Accepted on May 17th 2019