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APPLIED PROBLEMS
OF ARID LAND DEVELOPMENT

# Climate-Determined Changes of Organic Carbon Stocks in the Arable Chernozem of Kursk Region

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**Abstract**—Two biogeochemical simulation models describing carbon turnover in soil, the DeNitrification–DeComposition (DNDC) model and the Rothamsted Long-Term Field Experiment Carbon (RothC) model, have been parameterized in accordance with the conditions of arable leached chernozems of Kursk region and validated based on soil $CO_2$ emission measurement data at Kursk Biosphere Station, Institute of Geography, Russian Academy of Sciences, as a case study on five crops: winter wheat, barley, corn, sunflower, and potato. The modeling has served to reconstruct dynamics of organic carbon content in soil (SOC) over the period of 1990–2018. The RothC model generated the region-specific characteristics of SOC losses, which primarily depend on the weather conditions at an average rate of 342 ± 54 kg C/ha year. The outcomes of the DNDC model are more crop-specific and demonstrate maximal SOC losses under corn (272 kg C/ha year) and maximal accumulation under winter wheat (266 kg C/ha year). The period was characterized by a steady increase in heat supply, including the annual average air temperature (0.68°C/10 years) and growing degree-days (224°C day/10 years). The coefficients of variation of the precipitation and moisture indices in the region exceed 20% over the period. The arable chernozems of Kursk region is characterized by moderate and strong positive correlations between the SOC dynamics and thermal environment conditions including growing degree-days, Selyaninov hydrothermal coefficient, Sapozhnikova moisture index. The contribution of warm-period precipitation is less significant.

*Keywords:* agroclimatic resources, agro-ecosystems, organic carbon balance, simulation modeling, Land Degradation Neutrality, statistical analysis, emission of carbon dioxide

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## INTRODUCTION

The UN Convention to Combat Desertification (CCD) adopts the organic carbon (SOC) content in soil as one of the most significant indicators in the modern concept of the Land Degradation Neutrality (LDN) (Sustainable land ..., 2017). Model estimations of changes in SOC stocks can be used as an alternative to the direct measurement offered in the CCD system, which provides insufficient data on soil organic matter dynamics.

The active introduction of mathematical methods in geographical research allows the quantitative assessment of the flows of substances through landscapes, which depends on multiple, natural factors, primarily, climatic and anthropogenic factors (Cherkashin and Bibaeva, 2013). Mathematical models allow for computer experiments, which act as subjects of research (Priputina et al., 2016). However, the lack of field observations and the nonuniformity of methods to determine the soil organic matter are among the serious factors limiting the creation and development of such models (Chertov and Nadporozhskaya, 2016).

The anthropogenic-related loss of SOC is acknowledged to be primarily caused by intensive soil cultivation, the application of mineral fertilizers and a lack of organic fertilizers, melioration practices that are poorly substantiated in scientific term, the development of erosional and deflation processes, etc. (Kosolapov et al., 2015). Sustainable land-use practices are used to enhance SOC retention and accumulation in achieving the goals of the LDN concept (Sanz et al., 2017).

As for natural factors, the SOC dynamics is substantially affected by the climate, including temperature and moisture conditions in the region (Reichstein et al., 2005; Moyano et al., 2013). Researchers are unanimous in acknowledging the feedback between the carbon cycle and the climate, which is manifested by the impact of weather conditions on SOC stocks in terrestrial ecosystems and the soil (Friedlingstein et al., 2003). This is taken into account with the use of the special indices in the officially adopted methods (IPCC, 2006).

Kursk region lies in a zone of unstable moistening (Smol'yaninov and Starodubtsev, 2011) but as well in a region of the most intense rising of summer temperatures (*Vtoroi otsenochnyi doklad* ..., 2014). This is accompanied by the increased number of heat waves and precipitation-free days, which further reduces moisture indices in the area; the aridity of the climate increases (Sirotenko and Pavlova, 2012) and is undoubtedly reflected in the climate-conditioned SOC dynamics.

The goal of the present study was to assess the effect of climate conditions on dynamics of SOC stocks in arable soil. The objectives included the estimation of agroclimatic indicators of Kursk region for 1990–2018; the parameterization and validation of carbon simulation models for the conditions of the study region, the reconstruction of SOC dynamics over the same period, and correlation analysis of the climate change effects on the targeted indicator.

## MATERIALS AND METHODS

Research was carried out as a case study of arable chernozem at Kursk Biosphere Station (KBS) of the Institute of Geography, Russian Academy of Sciences (the village of Panino in Medvenka district of Kursk region: 51°54′ N, 36°10′ E), which is a geographical station located 20 km south of Kursk in the Central Chernozem economic region. The primary objective of KBS is long-term monitoring of the impact that various types of agricultural activities have on geosystems of the forest–steppe zone (Petrova, 2008).

The agroclimatic indices nessesary for characterization of the region were calculated with the database of Kursk weather station from the All-Russia Research Institute of Hydrometeorological Information of the World Data Center (Sirotenko and Pavlova, 2012). This included the average annual air temperatures ($T_{av}$), the temperatures in January ($T_{Jan}$) and July ($T_{Jul}$), the sums of positive temperatures ($\Sigma T > 0$) and temperatures above 5°C ($\Sigma T > 5$), growing degree-days above 10°C ($\Sigma T > 10$), the sums of the warm-season temperatures ($\Sigma T_{IV-IX}$) and summer temperatures ($\Sigma T_{VI-VIII}$), annual precipitation ($P_{year}$), precipitation of the cold ($P_{X-III}$) and warm seasons ($P_{IV-IX}$), summer precipitation ($P_{VI-VIII}$), Budyko index of dryness (ID), Selyaninov Hydrothermal Coefficient (HTC), Sapozhnikova Moisture Index (MI), and the potential evaporation according to L. Tyurk (1958) and S. Thornthwainte (1948).

Two biogeochemical simulation models describing SOC cycling in the soil, the DNDC and RothC models were applied in the study. They are widely used internationally and adequately reflect soil processes, according to the assessment of the International Soil Modeling Consortium (International Soil ..., 2019).

The RothC model (version 26.3) is a model of SOC turnover in non-waterlogged topsoil, which allows for the effects of soil type, temperature, moisture, and plant cover on the SOC dynamics and $CO_2$ emission (Jenkinson et al., 1987); changes in these factors serve as the model's output parameters. It uses a monthly time step.

The DNDC model (version 9.5) is a process-based model for the assessment of the main components of the carbon and nitrogen cycles in agricultural soils (Li et al., 1992). In addition to the characteristics listed for the first model, it takes into account details of crops management technologies, including their biomass, the planting and harvesting dates, the tillage operations, and the time and amount of fertilizer applications. The output data are formed with a daily time step and include changes of humus and humads pools in a soil profile at different depths and carbon input with plant residues, as well as the rates of photosynthesis and the respiration of plants and microorganisms, etc.

Due to the small number of input variables, the RothC model was parameterized within the framework of specified algorithms (Coleman et al., 1997); the indices were estimated according to prescribed equations. The internal parameters of the DNDC model were considerably modified based on the method reported and validated earlier with examples for KBS (Sukhoveeva and Karelin, 2019).

The characteristics of clay leached arable chernozems (Haplic Chernozem), which are common in the region, and their SOC and humus stocks were taken from the monograph by Lyuri et al. (2010). The soil levels of decomposable plant biomass and microbial biomass were determined earlier (Karelin et al., 2015, 2017). Information about crop yields and amount of fertilizer application rate was sourced from *Rosstat* (Unified interdepartmental..., 2019). The quantity of input plant residues was calculated with the Levin's method (Levin, 1977).

The modeling results were validated with field measurements of $CO_2$ emission from soil in 2017–2018 by the chamber method according to the principles developed earlier for assessment of the emission in grassland ecosystems (Karelin et al., 2015). Correlation analysis, one-way analysis of variance (ANOVA), as well as *F*-test of equality of two variances were used to evaluate the modelling effectiveness.

## RESULTS AND DISCUSSION

**Climatic conditions.** Analysis for the 1990–2018 period revealed steady trends in the average annual temperature and growing degree-days (Fig. 1a). The 29-year average annual temperature was 7.1°C in the region; the warming proceeds at a rate of 0.68°C/10 years, i.e., more rapidly than in the Central Federal District (0.62°C/10 years), European Russia (0.53°C/10 years),

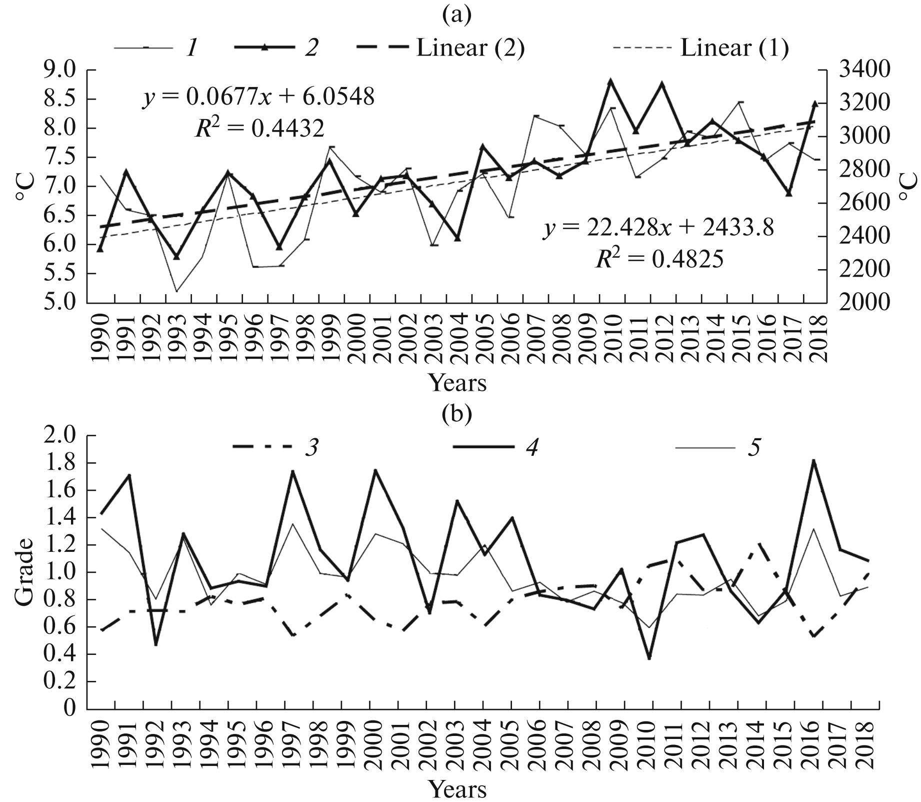


**Fig. 1.** Dynamics of agroclimatic conditions in Kursk region for 1990–2018 by (a) temperature and (b) moisture indices. (*1*) annual average air temperature, (*2*) growing degree-days with their linear trends, formulas, and determination coefficients; (*3*) Budyko ID; (*4*) Selyaninov HTC; and (*5*) Sapozhnikova MI.

and in the country overall (0.44°C/10 years) (Gruza and Ran'kova, 2012).

Average growing degree-days is 2770°C, and the heat supply increases by 224°C day/10 years, whereas in Russia average rate of the rising is 96°C day/10 years (*Vtoroi otsenochnyi doklad*..., 2014).

The annual precipitation in the region is equal to 642 mm, ranging from 458 mm in 2014 to 965 mm in 2016. The potential evaporation was estimated to be at least 479 mm (after Tyurk (1958)) and up to 653 mm (after Thornthwainte (1948)). The estimated 29-year averages for indices are as follows: Budyko ID = 0.8 (from 1.2 in 2014 to 0.5 in 2016), Selyaninov HTC = 1.1 (from 0.4 in 2010 to 1.8 in 2016), Sapozhnikova MI = 1.0 (from 0.6 in 2010 to 1.4 in 1997). This generally characterizes the moisture as sufficient (Fig. 1b). The indicators of moisture supply for plants, however, greatly vary. Thus, the coefficient of variation is 16% for annual precipitation, 24% for the precipitation of warm season, and 33% for the summer season. It is estimated at 20% for Budyko ID, 21% for Sapozhnikova MI, and 34% for Selyaninov HTC.

**Model validation.** For the RothC model verification to confirm the convergence of field and calculated values of $CO_2$ emission it was be solved to take into account mostly the equality of average values that may be proofed by one-way ANOVA, because small size of the samples ($n$ = 6–7 because the step of the model is one month) limits ability of using other methods. The differences in means were insignificant for all crops except corn.

Based on the outcomes of one-way ANOVA, validation of the DNDC model confirmed the equality between the mean field and estimated values of $CO_2$ emission from soils for all crops. Their variances were equal; the modeled and measured values were characterized by moderate and strong correlations. Therefore, all five crops were included in DNDC-based estimations.

**Dynamics of SOC.** For long-term period the RothC model predicts the average rate of SOC declining 342 ± 54 kg C/ga year. The estimated losses are 289 for winter wheat plots, 332 for barley, 341 for sunflower, and 407 kg C/ha year for potato. The DNDC-based estimates suggest the possible accumulation of 266 kg C/ha year of SOC in winter wheat agrocenoses, whereas for spring crops, i.e. sunflower, potato, barley, and corn, the rate of losses is 86, 160, 240, and 272 kg C/ha year, respectively.

The produced quantitative assessments of SOC decline in the arable chernozem of Kursk region corresponds to the findings of other researchers. According to Kosolapov

**Table 1.** Model verification based on field observations of $CO_2$ emission from soil (Kursk Biosphere Station, Institute of Geography, Russian Academy of Sciences)

| Model | Criteria | Crops | Potato | | Corn | Winter wheat | | Sunflower | Barley |
|---|---|---|---|---|---|---|---|---|---|
| | | year | 2017 | 2018 | 2018 | 2017 | 2018 | 2017 | 2017 |
| RothC | Correlational analysis | $r_p$ | 0.931 | 0.652 | 0.577 | 0.552 | 0.633 | 0.302 | –0.022 |
| | | $P$ | 0.002 | 0.161 | 0.230 | 0.199 | 0.177 | 0.510 | 0.963 |
| | | $n$ | 7 | 6 | 6 | 7 | 6 | 7 | 7 |
| | One-way ANOVA | $F$ | 3.068 | 2.019 | 7.816 | 0.814 | 0.624 | 2.239 | 1.164 |
| | | $F_{cr}$ | 4.747 | 4.965 | 4.965 | 4.747 | 4.965 | 4.747 | 4.747 |
| | | $P$ | 0.105 | 0.186 | 0.019 | 0.385 | 0.448 | 0.160 | 0.302 |
| | *F*-test of the equality of two variances | $F$ | 0.811 | 1.460 | 0.160 | 0.327 | 0.617 | 0.305 | 0.600 |
| | | $F_{cr}$ | 0.233 | 5.050 | 0.198 | 0.233 | 0.198 | 0.233 | 0.233 |
| | | $P$ | 0.403 | 0.344 | 0.032 | 0.100 | 0.305 | 0.087 | 0.275 |
| DNDC | Correlational analysis | $r_p$ | 0.300 | 0.336 | 0.772 | 0.531 | 0.424 | 0.662 | 0.533 |
| | | $P$ | 0.259 | 0.204 | <0.001 | 0.028 | 0.101 | 0.005 | 0.028 |
| | | $n$ | 16 | 16 | 16 | 17 | 16 | 16 | 17 |
| | One-way ANOVA | $F$ | 1.020 | 5.119 | 0.001 | 0.591 | 2.068 | 1.405 | 0.975 |
| | | $F_{cr}$ | 4.171 | 4.171 | 4.171 | 4.149 | 4.171 | 4.171 | 4.149 |
| | | $P$ | 0.321 | 0.031 | 0.991 | 0.448 | 0.161 | 0.245 | 0.331 |
| | *F*-test of the equality of two variances | $F$ | 4.559 | 1.331 | 1.763 | 4.989 | 14.695 | 1.707 | 1.186 |
| | | $F_{cr}$ | 2.403 | 2.403 | 2.403 | 2.333 | 2.403 | 2.403 | 2.333 |
| | | $P$ | 0.002 | 0.293 | 0.142 | <0.001 | <0.001 | 0.156 | 0.368 |

The gray background denotes cells in which the values of the criteria prove agreement between the observed and calculated values.

et al. (2015) and based on The State National Report (*Gosudarstvennyi (natsyonal'nyi) doklad*..., 2014), a negative humus balance has been forming in the top layer of the forest–steppe zone soils of Central Chernozem economic region due to their high respiration; its losses are estimated at 0.7–0.9 t/ha year, which corresponds to a SOC decline by 406–522 kg C/ha year in the region, because, according to our estimates, in investigated soils humus contains 58% of carbon. These losses are slightly less than the annual average SOC losses on croplands of Russia over 1990–2004 as estimated with the balancing method at 610 kg C/ha year (Romanovskaya and Karaban', 2007).

Comparison of the carbon dynamics under different crops with the DNDC model revealed a comparable accumulation at a rate of 250 kg C/ha year under winter wheat in cereal–fallow crop rotation on the gray forest soils of Moscow region (Sapronov, 2008). The SOC losses were more considerable (1004 kg C/ha year) on sod podzolic soils under potato without fertilizers in Vladimir region, whereas the soil carbon balance reached 6016 kg C/ha year with the use of fertilizers (Lukin, 2015). Its losses were estimated at 1967–3701 kg C/ha year on fallow leached chernozem in Priob'e, depending on input of plant residues of wheat and cover crops (Vlasenko et al., 2009).

Based on the findings of graphical analysis, the RothC method reflects the region-specific characteristics of carbon losses from agricultural soils; their annual values are nearly identical among different crops (Fig. 2a). The outcomes of DNDC modeling are more specific and differences between crops are significant (Fig. 2b). Such crops-specificity of DNDC is quite admissible because the plants differ significantly in their effect on process of SOC mineralization: the most its losses are observed under fallow and row crops, moderate ones under grain crops and annual grasses, and under perennial grasses its stocks don't decrease (Kosolapov et al., 2015).

The irregular and insufficient application of organic fertilizers should be considered to be the most likely factor in SOC stock decline. Thus, according to *Rosstat* (Unified interdepartmental..., 2019), as little as 0.8 t/ha year was applied on average in Kursk region in 1993–2018. In recent years for row crops this amount decreased in 10 times in comparison with mean over 26 years. Over this period, the fertilizers were applied nine times under potatoes and seven times under sunflowers. Ultimately, this will lead to a decline in potentially mineralizable carbon content (Semenov and Tulina, 2011).

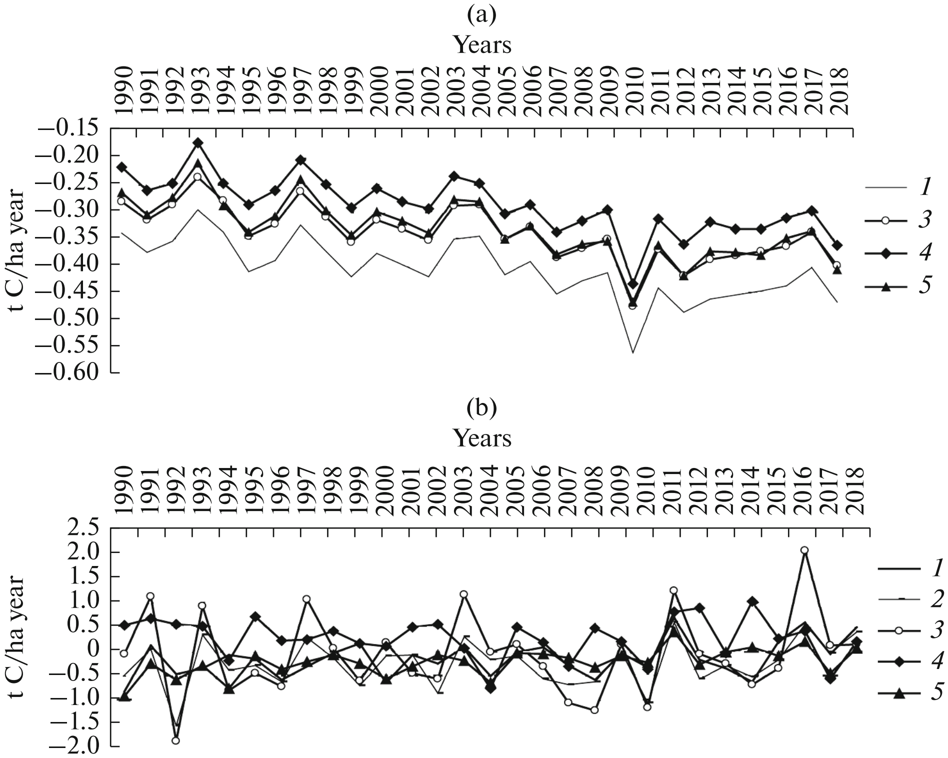


**Fig. 2.** Assessment of organic carbon dynamics in arable leached chernozem under different crops based on (a) RothC and (b) DNDC models. (*1*) potato (*2*) corn; (*3*) sunflower; (*4*) winter wheat; and (*5*) barley.

**Dependence of SOC loss on climatic conditions.** Strong positive correlations are observed between the SOC balance estimated based on the RothC model and the thermal conditions, i.e., different sums of temperatures and potential evapotranspiration (Table 2). The negative relationships between the carbon dynamics and the warm-season precipitation, Selyaninov HTC, and Sapozhnikova MI are rather interesting. In arable chernozems generally formes a specific moisture regime, under which the moisture content in soils is observed to be the highest in spring and fall against a lower temperature background (*Russkii chernozem*, 1983). However, according to the algorithm used in this model (Coleman et al., 1997), under such a significant clay content (56%) and high maximum soil moisture deficit (61 mm), the soil retains water even if there is insufficient atmospheric moistening during the summer period and, as a consequence, the SOC losses through soil respiration remain high.

The DNDC estimation of SOC losses demonstrate weak positive relationships with the temperature for soil under barley and with the moisture characteristics under sunflowers (Table 2). No significant dependences were identified between these parameters for wheat. Strong positive correlations are typical for Selyaninov HTC and SOC stocks dynamics under row crops, i.e., corn and sunflower, which have the most water demand.

On one hand, the temperature does have a primary effect on the rate of organic matter decomposition (Reichstein et al., 2005). Since the latter, along with the moisture, depends on the substrate characteristics, the more easily organic matter decomposes, the more sensitive is the rate of this process to hydrothermal conditions (Kirschbaum and Mueller, 2001).

On the other hand, the identified dependences arise from the fact that the majority of current biogeochemical models present the mechanisms of the response of the carbon cycle components in soil to temperature and moisture variations in the form of simple empirical nonlinear function (Davidson et al., 2006). The van 't Hoff and Arrhenius equations used in them systematically underestimate the SOC decomposition rate under low temperatures and overestimate them under high temperatures, since the effect of weather conditions under their deviation from the optimum occurs due to the change in activity of the soil microbiota and the rate of biochemical processes. In agrolandscapes the temperatures optimal for microorganisms (35–45°C) observed in the season of insufficient humidity and, therefore, do not affect the rate of organic matter decomposition (Alekseeva and Fomina, 2015).

**Table 2.** Pearson correlation coefficients between changes in climatic indices and dynamics of organic carbon stocks in arable leached chernozems in Kursk region over 1990–2018 ($n = 29$, $P < 0.05$)

| Model | RothC | | | | DNDC | | | |
|---|---|---|---|---|---|---|---|---|
| climatic indices | crop | | | | | | | |
| | potato | sunflower | wheat | barley | potato | corn | sunflower | barley |
| $T_{av}$ | 0.792 | 0.802 | 0.799 | 0.804 | –* | – | – | – |
| $T_{Jul}$ | 0.739 | 0.731 | 0.699 | 0.683 | – | – | – | 0.420 |
| $\Sigma T > 0$ | 0.984 | 0.990 | 0.988 | 0.992 | – | – | – | 0.444 |
| $\Sigma T > 5$ | 0.978 | 0.985 | 0.983 | 0.988 | – | – | – | 0.431 |
| $\Sigma T > 10$ | 0.938 | 0.941 | 0.933 | 0.950 | 0.414 | – | – | 0.602 |
| $\Sigma T_{IV–IX}$ | 0.980 | 0.977 | 0.980 | 0.979 | – | – | – | 0.543 |
| $\Sigma T_{VI–VIII}$ | 0.905 | 0.891 | 0.884 | 0.855 | – | – | – | 0.513 |
| Evaporation by Thornthwainte | 0.996 | 0.996 | 0.984 | 0.985 | – | – | – | 0.478 |
| Evaporation by Tyurk | 0.792 | 0.802 | 0.799 | 0.804 | – | – | – | – |
| $P$ | – | – | – | – | – | – | 0.442 | – |
| $P_{IV–IX}$ | –0.419 | –0.414 | –0.475 | –0.471 | – | 0.402 | 0.534 | – |
| $P_{VI–VIII}$ | – | – | – | – | – | – | 0.850 | – |
| $P_{X–III}$ | – | – | – | – | 0.438 | – | – | – |
| Budyko DI | 0.636 | 0.636 | 0.648 | 0.656 | – | – | – | 0.454 |
| Selyaninov HTC | –0.424 | –0.414 | –0.457 | –0.430 | – | 0.741 | 0.839 | – |
| Sapozhnikova MI | –0.603 | –0.601 | –0.660 | –0.659 | – | 0.451 | 0.569 | – |

Moderate correlations ($0.4 \le r_p \le 0.7$) are shown against the light-gray background, and strong correlations ($r_p > 0.7$) are show in dark-gray; * no significant correlation.

## CONCLUSIONS

The steady upward trend of heat supply was observed in Kursk region in 1990–2018 against the backgrownd of unstable moisture supply.

The parameterized RothC and DNDC models can be applied in Kursk region to assess dynamics of organic carbon stocks in arable chernozems.

The RothC model produces the region-specific characteristics of SOC losses which are depending on the climatic conditions primarily. Whereas the outcomes of the DNDC model mostly characterize the effect of individual crops on organic carbon stocks.

The SOC dynamics estimated with both models demonstrates strong positive correlations with the thermal characteristics of the environment.

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## COMPLIANCE WITH ETHICAL STANDARDS

*Conflict of Interest*. The authors declare that they have no conflict of interest

*Statement on Animal Welfare*. This article does not contain any studies involving animals performed by any of the authors.

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