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Experimental and Model Estimates of Respiration of the Forest Sod-Podzolic Soil in the Prioksko-Terrasny Nature Reserve

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Abstract—Modeling the carbon cycle in forests is often restricted by modeling the main components, including emissions (respiration of soils and debris) and production (deposition of carbon in plants and soils). In this study we examine the applicability of various versions of the T&P model to estimate monthly, seasonal, and annual fluxes of CO_2 from the sod-podzolic soil in the mixed forest of the Prioksko-Terrasny Nature Reserve, Moscow oblast. The model is parameterized and verified, and the accuracy is tested using a database of 20 years of monitoring CO_2 emissions from soils and independent weather variables, including mean monthly air temperature and monthly precipitation. Numeric experiments show that all versions of the T&P model (both initial and parameterized by training sets at different temporal intervals) satisfactorily describe the long-term dynamics of mean monthly respiration of the sod-podzolic soil under forest cover (*SRm*). Parameterization of the T&P model with experimental data as a training set practically does not improve the quality of modeling in any of the test intervals. The use of weather data averaged over 20 years for the calculation of *SRmod-mean* and estimates of seasonal and annual soil fluxes of CO_2 on their basis (*SeSRmod-mean*) in most cases overestimates the corresponding experimentally obtained values (*SeSRexp*). *SeSRmod-mean* for annual, summer, and winter soil CO_2 fluxes are on average 4.5–6.7% higher than *SeSRexp*, and *SeSRmod-mean* for the warm season shows an overestimation of approximately 3%. The largest discrepancy of calculated estimates to experimental data is found for the spring period: the overestimation amounts to ~22%. Thus, the use of weather data averaged over 20 years has shown the applicability of an ensemble of versions of the T&P model for estimating seasonal and annual fluxes of CO_2 from soil in a humid continental climate.

Keywords: soil CO_2 emission, empiric modeling, weather parameters, forest ecosystems, humid continental climate, parameterization, verification, accuracy of modeling

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INTRODUCTION

Being the most widespread terrestrial ecosystems on our planet, forests play a decisive role in biodiversity conservation, supporting the existence of more than half of all known plant and animal species (Bukvareva et al., 2015; Gauthier et al., 2015; Lukina et al., 2015). In the global biogeochemical carbon cycle (C), the role of forest ecosystems is no less important: they provide the main part of the carbon sink to terrestrial ecosystems and are considered today the main climate-stabilizing systems of the earth's surface (Zamolodchikov et al., 2007, 2011, 2017, 2018; Le Quere et al., 2014; Shvidenko and Shchepashchenko, 2014). The decisive influence on the functioning and sustainability of forest ecosystems, including all components of the biogenic carbon cycle, is exerted by various environmental factors, primarily climatic ones (Lal, 2005; Vygodskaya et al., 2009; Kurganova et al., 2011b, 2017; Karelin et al., 2017). Forest ecosystems are unique in their diversity and complexity of interactions between their individual components. In this regard, mathematical models of forest ecosystems are quite complex and can be presented as a metamodel, i.e., a set of some simplifying methodological principles (Isaev et al., 2011). Thus, in accordance with the ideas of A.S. Isaev, "the simplest approach to the mathematical description of a forest ecosystem is to mark out a single component of the ecosystem that is of interest to researchers and build a model of its dynamics" (cited by Isaev et al., 2011). Applying this principle, the construction of models of the carbon cycle in forest ecosystems can be reduced to developing models of its main components—emission (respiration of soil and wood debris) and production (carbon deposition in vegetation and soils).

CO_2 emission from soils in forest ecosystems (or soil respiration, *SR*) is characterized by high temporal and spatial variability (Kurganova et al., 2003, 2011a, 2017; Karelin et al., 2014, 2017; Zamolodchikov et al., 2017). The main abiotic parameters that control the the emission component of the carbon cycle are air and soil temperatures, as well as the level of soil moisture, which is mainly determined during the growing season by the amount of precipitation (Wang et al., 2010; Osipov, 2013; Song et al., 2014; Liu et al., 2017). The analysis of data from the long-term monitoring of CO_2 emissions from soils of forest ecosystems in southern Moscow oblast showed that the main predictor of monthly CO_2 fluxes from soils was soil temperature, and the main factors that control the total annual CO_2 emissions from soils were the total precipitation over the spring–summer period (Kurganova et al., 2011a) and the value of the summer hydrothermal coefficient (Kurganova et al., 2017).

An experimental determination of annual CO_2 fluxes from soils is a very laborious process, so a more rational and promising way to obtain numerical estimates of soil respiration is to use mathematical models of varying complexity: from simple empirical models (Reichstein et al., 2003; Kurganova et al., 2011a; Karelin et al., 2014; Ivanov et al., 2018) to dynamic ones (Komarov et al., 2007; Chertov and Nadporozhskaya, 2016). As a rule, most empirical models use soil or air temperature as the main predictor for the numerical estimate of *SR*, and the most commonly used function for estimating the temperature response of soil respiration within its annual dynamics is the Van't Hoff function, which is called the temperature coefficient Q_{10} (Kätterer et al., 1998; Janssens and Pilegaard, 2003). There is evidence that the temperature response of *SR* (or Q_{10} coefficient) is not constant for the same ecosystem and depends on the temperature range and moisture conditions in which *SR* was empirically determined (Janssens and Pilegaard, 2003; Lopes de Gerenyu et al., 2005; Zheng et al., 2009; Kurganova et al., 2012, 2018). Another approach that makes it possible to describe the global *SR* distribution at a monthly averaging level with consideration for moisture conditions was proposed by American researchers J. Raich and C. Potter in 1995. This is the so-called *T&P model* (Raich and Potter, 1995; Raich et al., 2002), in which the mean monthly air temperature and monthly precipitation are used as independent variables. This model was previously applied in various modifications to assess the global distribution of soil respiration (Reichstein et al., 2003; Chen et al., 2010; Hashimoto et al., 2015) and has practically not been used to numerically estimate the long-term dynamics of CO_2 emissions from soils in individual ecosystems.

The main goal of the present study was to analyze the applicability of various versions of the T&P model for the numerical estimate of monthly, seasonal, and annual CO_2 fluxes from the sod-podzolic soil in the mixed forest of the Prioksko-Terrasny Nature Biosphere Reserve. Parameterization of the model, its subsequent verification, and an estimation of the modeling accuracy were carried out based on the data of the year-round 20-year monitoring of CO_2 emissions from the soil using the main meteorological characteristics (mean monthly air temperature and monthly precipitation) as independent variables.

MATERIALS AND METHODS

General Characteristics of Climate, Vegetation, and Soils

The studies were carried out on the territory of the Prioksko-Terrasny State Nature Biosphere Reserve (the southern part of Moscow oblast, 54°55′ N, 37°34′ E) in a mixed forest with a well-developed herbaceous cover. The stand is represented by the Scots pine (*Pinus sylvestris* L.), small-leaved linden (*Tilia cordata* Mill.), Eurasian aspen (*Populus tremula* L.), and oak (*Quercus robur* L.) (4P3Ln2As1B un. O) (whose age reaches 90–120 years). The soil of the plot is sod–weakly podzolic (*Retisols*). The study area belongs to the zone of temperate continental climate. According to the data of long-term meteorological observations (the Complex Background Monitoring Station, settlement of Danki, Serpukhov district, Moscow oblast), the mean annual air temperature in 1973–2017 in the study area was 5.2 ± 0.2°C, and the mean annual precipitation was 671 ± 17 mm. Selyaninov's hydrothermal coefficient (HTC) for the summer period (June to August) varied from 0.70 to 2.40, and its average long-term value was 1.50 ± 0.07.

The studied soil (the 0–10 cm layer) is a sandy loam texture (sand : silt : clay = 11.6 : 1.0 : 1.3) and has an acidic reaction of the soil suspension (pH_{KCl} = 3.67 ± 0.02). The content of organic carbon (C_{org}) and total nitrogen (N) is low and amounts to 12.2 ± 2.8 g C kg^{-1} of soil and 0.96 ± 0.15 g N kg^{-1} of soil, respectively (C : N ratio = 15.3). The soil has a well-formed litter with a thickness of 2–4 cm, in which the C reserve is 0.58 ± 0.03 kg C m^{-2}.

Determination of CO_2 Emissions from Soil

CO_2 emissions from soil (or soil respiration, *SR*) were determined continuously for 20 years (1998–2017) at 7–10 d intervals, by the closed chamber method (Lopes de Gerenyu et al., 2001; Kurganova et al., 2003). Carbon dioxide emissions from soils were calculated according to the formula

$$SR = (C_2 - C_1)\,Ht^{-1}, \quad (1)$$

where *SR* is the CO_2 emission, mg C m^{-2} h^{-1}; C_2 and C_1 are the final and initial concentration of CO_2 inside the isolator, mg C m^{-3}; *H* is the height of the isolator above the soil surface, m; and *t* is the exposure time, h.

Table 1. Initial parameters (Raich and Potter, 1995; Raich et al., 2012) and parameters adjusted on the basis of training samples for different versions of the T&P model

Model	R_o	Q	K	Source
T&P-1	1.334	0.0399	1.634	Raich and Potter, 1995
T&P-2	1.250	0.0545	4.259	Raich et al., 2002
T&P-3′	1.162	0.0509	1.501	Training sample, 1998–2007
T&P-3″	0.961	0.0481	1.496	Training sample, 2008–2017

It was assumed in the calculations that the CO_2 concentration in the chamber increased linearly in the first 30 and 90 min in the warm (May to October) and cold (November to April) periods, respectively.

The value of the mean monthly intensity of soil respiration (*SRm*, g C m^{-2} day^{-1}) was calculated as the arithmetic mean of all measurements carried out for each month. The total monthly CO_2 fluxes of soils (g C m^{-2} $month^{-1}$) were calculated taking into account the duration of the corresponding month. Seasonal and annual CO_2 fluxes from soils (season soil respiration, *SeSRexp*, g C m^{-2}) were obtained by summing the corresponding monthly fluxes.

Parameterization of the Models for Estimating the Mean Monthly Intensity of CO_2 Fluxes from Soils (SRm)

The value of *SRm* was numerically estimated using the nonlinear T&P model proposed by Raich and Potter (1995), in which the independent variables are the mean monthly air temperature (*Ta*, °C) and the monthly total precipitation (*P*, cm). The necessary climatic data for the entire observation period were kindly provided by the staff of the Background Monitoring Station (Danki-Zapovednik settlement, Serpukhov district, Moscow oblast), which is located on the territory of the Prioksko-Terrasny Nature Reserve.

The T&P model for assessing the mean monthly intensity of CO_2 release from soils (*SRm*, g C m^{-2} day^{-1}), based on the mean monthly air temperature (*Ta*, °C) and the amount of precipitation for the corresponding month (*P*, cm), has the following form (Raich and Potter, 1995):

$$SRm = R_0 e^{QTa}\left(P/(K+P)\right), \tag{2}$$

where R_0 (g C m^{-2} day^{-1}) is soil respiration at 0°C in the absence of moisture limitation; Q (°C^{-1}) is the exponential relationship between soil respiration and temperature, and K (cm) is the constant of self-saturation in the hyperbolic relationship between *SRm* and monthly precipitation. The following model parameters were originally proposed (T&P-1; Raich and Potter, 1995): $R_0 = 1.334$ g C m^{-2} day^{-1}, $Q = 0.0399$°C^{-1}, and $K = 1.634$ cm. In the next version (T&P-2; Raich et al., 2002), the value of the parameter R_0 slightly decreased (Table 1), but parameters Q and K increased significantly (by ~1.4 and ~2.6 times, respectively).

The resulting array of empirical data (general sample), based on which the parameterization of the T&P model and its subsequent testing were carried out, included 240 records (12 months × 20 years) and was divided into two training samples with 120 records in each, which corresponded to two time periods: 1998–2007 and 2008–2017. The parameters R_0, Q, and K (versions T&P-3′ and T&P-3″, Table 1) were calculated separately for each of these samples using the R program (R Core Team, 2018).

Estimating the Accuracy of Modeling the Mean Monthly Soil Respiration SRm

The data arrays that were not included in the training set were cross used as test samples, which served to test the reparameterized versions of the T&P model (T&P-3′ and T&P-3″). The initial versions of T&P-1 and T&P-2 were tested both based on a general set of empirical data and alternately for the above-indicated time intervals (1998–2007 and 2008–2017). The accuracy of modeling the SRm value was estimated using Theil's "mismatch coefficient" (T) in accordance with the formula (Shitikov et al., 2003):

$$\mathrm{T} = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_{\mathrm{real}} - X_{\mathrm{model}})^2}}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}X_{\mathrm{real}}^2} + \sqrt{\frac{1}{N}\sum_{i=1}^{N}X_{\mathrm{model}}^2}}, \tag{3}$$

where X_{real} is the real (measured) values of monthly CO_2 fluxes and X_{model} is the modeled (calculated) values of *SR*. The values of coefficient T are in the range [0; 1], and the closer coefficient T is to zero, the more accurate the modeling is. The threshold of its significance in studying natural processes is 0.3 (Theil, 1971); i.e., the modeling results must be recognized as correct at $T \leq 0.3$.

Other indicators of modeling accuracy were also as follows: the proportion of the explained variance (or the coefficient of determination, R^2) and the regression coefficient (the multiplier for the independent variable, which makes it possible to estimate how much the model underestimates or overestimates the experimental data), which were determined by the least squares method. That is, if the values of R^2 are sufficiently high, but the values of the regression coefficient significantly differ from 1, the work of the model cannot be considered satisfactory.

Accuracy of Assessing Seasonal and Annual CO_2 Fluxes from Soil

By analogy with the experimental data, estimates of seasonal and annual CO_2 fluxes from soils (*SeSRmod*, g C m^{-2}) were obtained on the basis of monthly CO_2 fluxes from soils that were calculated using various versions of the T&P model (*SRmod*, g C m^{-2} $month^{-1}$) by a simple summing of the corresponding monthly fluxes. We determined the precision assessment (*PrAs*, %) of total CO_2 fluxes for individual periods based on the relative difference between the estimates (calculated values) of *SeSRmod* using different versions of the T&P model and the experimentally determined value (*SeSRexp*):

$$PeAs(\%) = (SeSRmod - SeSRexp)/SeSRexp \times 100\%. \quad (4)$$

Negative values of *PrAs* correspond to an underestimation of *SeSRexp* using one or another version of the model, while positive values indicate overestimation of *SeSRexp*.

In addition, the assessment of seasonal and annual CO_2 fluxes from soil (*SeSRmod-mean*, g C m^{-2}) was carried out on the basis of calculating *SRm* with the help of four versions of the T&P model and using the averaged values of weather parameters (*Ta-mean* and *P-mean*) as independent variables for the same time period when the experimental observations were carried out, i.e., for 1998–2017.

RESULTS AND DISCUSSION

Temporal Heterogeneity of Monthly, Seasonal, and Annual CO_2 Fluxes from the Sod-Podzolic Soil

The long-term observations of carbon dioxide emissions from the sod-podzolic soil made it possible not only to characterize the magnitude of monthly, seasonal, and annual CO_2 fluxes, but also carry out a detailed statistical analysis of their time dynamics (Table 2). Considering that the temperature factor determines the intra-annual dynamics of soil respiration in the zone of temperate continental climate, it is quite expected that the minimum monthly CO_2 fluxes from soils were typical for all winter months and March and amounted to 14.4–18.7 g C m^{-2} $month^{-1}$. In the summer period, CO_2 emission from soils was 3–5 times higher, reaching a maximum value (72.2 g C m^{-2} $month^{-1}$) in July, when the weather conditions were the most favorable (on average) for the functioning of microbial communities and there was an active respiratory process of the root systems of plants. The highest interannual variability (CV) of monthly CO_2 fluxes from soils was recorded from December to March (CV = 44–55%), which is due to the high interannual dynamics of weather conditions (temperature conditions and time of the formation and destruction of snow cover) in the study region in this period of the year in recent decades (Kurganova et al., 2017). The interannual variability of monthly CO_2 fluxes in the rest of the year was 24–33% (Table 3), and it was slightly higher only in August (39%), which is quite explainable by the influence of summer droughts, the frequency of which over the last 20 years, coinciding with the period of observations over CO_2 fluxes from soils, increased significantly (Kurganova et al., 2017).

The mean long-term total CO_2 fluxes from soils in the summer season were almost four times higher than in winter (190 versus 51 g C m^{-2} $month^{-1}$). Autumn CO_2 fluxes from soils exceeded spring ones by 1.3 times, which is explained by active decomposition of litter in October to November, the prolongation of the snowless period, and the most pronounced trend of air temperature increase in the autumn months (~1.2°C over 10 years) compared to all other seasons over the years of observations (Kurganova et al., 2017). The interannual variability of winter CO_2 fluxes from soils was the highest and amounted to 36%, while it varied from 24 to 27% in all other seasons (Table 3). The mean long-term annual CO_2 flux from the sandy loamy sod-podzolic soil was 437 ± 20 g C m^{-2} $year^{-1}$, and its interannual variability due to differences in weather conditions was 21%.

An analysis of the share of seasonal CO_2 fluxes to annual CO_2 fluxes in long-term dynamics showed that the contribution of the winter season to the annual CO_2 flux from soils was on average 12% and the contribution of the summer season was slightly less than half—43%. The share of summer fluxes varied slightly (CV = 11%), while the variability of the contribution of the winter season was maximum—27%. The shares of the spring and autumn seasons accounted for 1/5 and 1/4 of the annual CO_2 emissions, respectively, and the variability of these shares was 20–23%. The share of the warm period (May–October) in the annual CO_2 flux from soils was the least affected by weather conditions (CV = 7%).

Testing and Accuracy of Different Versions of the T&P Model for Assessing SRm

The parameters for the T&P model that were calculated on the basis of experimental data in various training samples had rather close values and differed most of all in the value of R_0 (Table 1): the value of this parameter for the second training sample (2008–2017) was 20% less than for the first training sample (1998–2007). We noted earlier that the last two decades (1998–2017) were characterized by an increase in climate aridity in the studied region (Kurganova et al., 2017), which was

Table 2. Main statistical parameters that characterize the temporal variability of monthly, seasonal, and annual CO_2 fluxes from the sod-podzolic soil and the share of seasonal fluxes to the annual flux

Period	Min.	Max.	Scatter	Median	Mean	STD**	SE	CI	CV, %
Monthly CO_2 fluxes, g C^{-2} month^{-1}									
January (I)	5.4	40.9	35.5	16.2	**17.7**	9.8	2.1	4.6	**55**
February (II)	4.3	32.5	28.2	14.3	**14.4**	6.3	1.4	3.0	**44**
March (III)	2.2	33.1	31.0	16.0	**17.0**	8.6	1.9	4.0	**51**
April (IV)	15.2	34.5	19.2	23.7	**24.4**	5.9	1.3	2.7	**24**
May (V)	22.3	73.3	50.9	42.9	**44.2**	13.8	3.0	6.4	**31**
June (VI)	36.8	89.5	52.7	49.3	**56.0**	17.3	3.8	8.1	**31**
July (VII)	37.1	110.3	73.2	75.8	**72.2**	19.5	4.3	9.1	**27**
August (VIII)	24.8	101.2	76.5	59.3	**61.8**	23.8	5.2	11.1	**39**
September (IX)	23.8	65.7	41.9	47.8	**47.9**	14.2	3.1	6.6	**30**
October (X)	17.8	59.2	41.4	39.6	**38.9**	13.0	2.8	6.1	**33**
November (XI)	12.5	38.6	26.1	24.4	**24.1**	7.5	1.6	3.5	**31**
December (XII)	6.6	34.4	27.8	15.8	**18.7**	8.8	1.9	4.1	**47**
Seasonal CO_2 fluxes, g C^{-2} season^{-1}									
Winter (XII, I–II)	19	106	87	47	**51**	18	4	9	**36**
Spring (III–V)	46	130	85	85	**86**	22	5	10	**26**
Summer (VI–VIII)	121	301	180	186	**190**	51	11	24	**27**
Autumn (IX–XI)	59	163	103	115	**111**	30	7	14	**27**
Cold period (XI–IV)	68	192	123	114	**116**	29	6	13	**25**
Warm period (V–X)	216	492	276	321	**321**	77	17	36	**24**
Annual period (I–XII)	305	630	326	452	**437**	93	20	43	**21**
Share of seasonal fluxes with respect to the annual flux, %									
Winter (XII, I–II)	4	18	14	11	**12**	3.2	0.7	1.5	**27**
Spring (III–V)	13	29	16	19	**20**	4.5	1.0	2.1	**23**
Summer (VI–VIII)	32	54	22	43	**43**	4.8	1.0	2.2	**11**
Autumn (IX–XI)	16	38	22	24	**25**	5.1	1.1	2.4	**20**
Cold period (XI–IV)	15	34	19	27	**27**	4.8	1.1	2.3	**18**
Warm period (V–X)	66	85	19	73	**73**	4.8	1.1	2.3	**7**

* The parameters are based on 20-year monitoring data;

** STD is the standard deviation, SE is the standard error of the mean, CI is the confidence interval of the mean, and CV is the coefficient of variation.

Table 3. Proportion of variance explained (R^2), regression coefficients (a), and Tail's mismatch coefficient (T) for different versions of the T&P model and two test samples: 1998–2007 and 2008–2017

Parameter	T&P-1		T&P-2		T&P-3″	T&P-3′
	1998–2007	2008–2017	1998–2007	2008–2017	1998–2007	2008–2017
R^2	0.72	0.64	0.72	0.64	0.74	0.65
a	1.01	0.73	0.64	0.5	1.31	0.76
T	0.180	0.167	0.191	0.274	0.181	0.188

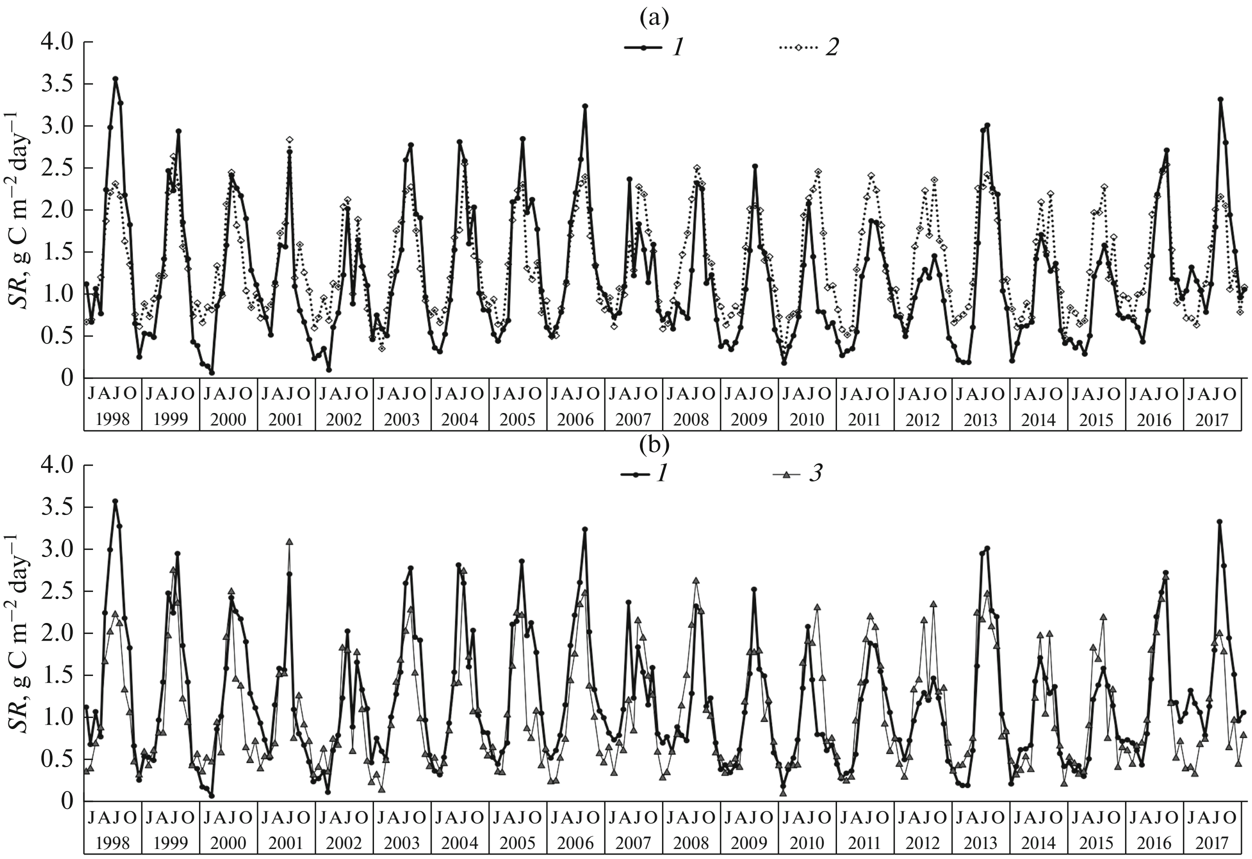

Fig. 1. Long-term dynamics of experimentally determined values of the average monthly soil respiration rate (*SR*) and the corresponding calculated estimates based on the initial versions of the T&P models: T&P-1 (a) and T&P-2 (b). (*1*) *SRexp*, (*2*) *SRmod* according to the T&P-1 version, and (*3*) *SRmod* according to the T&P-2 version.

the main reason for negative trends of changes in summer and annual CO_2 fluxes from the sod-podzolic soil under forest cover (Kurganova et al., 2017). Apparently, it was this tendency that was the cause of the differences in the value of the parameter R_0 between the two training samples. Nevertheless, the model parameters for the T&P-3′ and T&P-3″ versions that were calculated on the basis of the experimental data differed most significantly from the initial T&P-1 version in the value of temperature coefficient *Q* and from the T&P-2 version in the value of the *K* coefficient responsible for the relationship with precipitation.

These numerical experiments show that various initial versions of the T&P model for the entire volume of experimental data adequately describe the average monthly respiration rate of the sod-podzolic soil under the canopy of a mixed forest (Fig. 1). Although the proposed versions could both overestimate (usually in the winter months) and underestimate (in the summer) the experimentally obtained *SRm* values, the intra- and interannual dynamics of CO_2 emissions from soils were generally reflected correctly, and the values of *T* did not exceed 0.3. Meanwhile, the first version of the T&P model showed a higher accuracy ($T = 0.167$) compared to the later version T&P-2 ($T = 0.237$).

Within the framework of this study, we also estimated the accuracy of the initial versions—T&P-1 and T&P-2—as well as the versions parameterized on the basis of experimental data—T&P-3′ and *T&P-3″*—for the test samples that include the results of measurements for 1998–2007 and 2008–2017 (Fig. 2, Table 3). All versions of the T&P model demonstrated a quite satisfactory quality of correspondence of the calculated data to the experimental ones—coefficient *T* did not exceed the critical value of 0.3. The highest modeling accuracy was shown by the T&P-1 version, and the parameterization of the existing versions of the T&P model almost did not improve the quality of modeling in any of the test intervals (Table 3). The T&P-2 version showed the lowest agreement between the calculated and experimental data (T = 0.191–0.274), greatly overestimating the measurement results.

The share of explained variance was slightly higher when testing all versions of the T&P model based on the first data array (Fig. 2a) compared to the second one (Fig. 2b). The distribution of residues that represent the difference between *SRexp* and *SRmod* did not

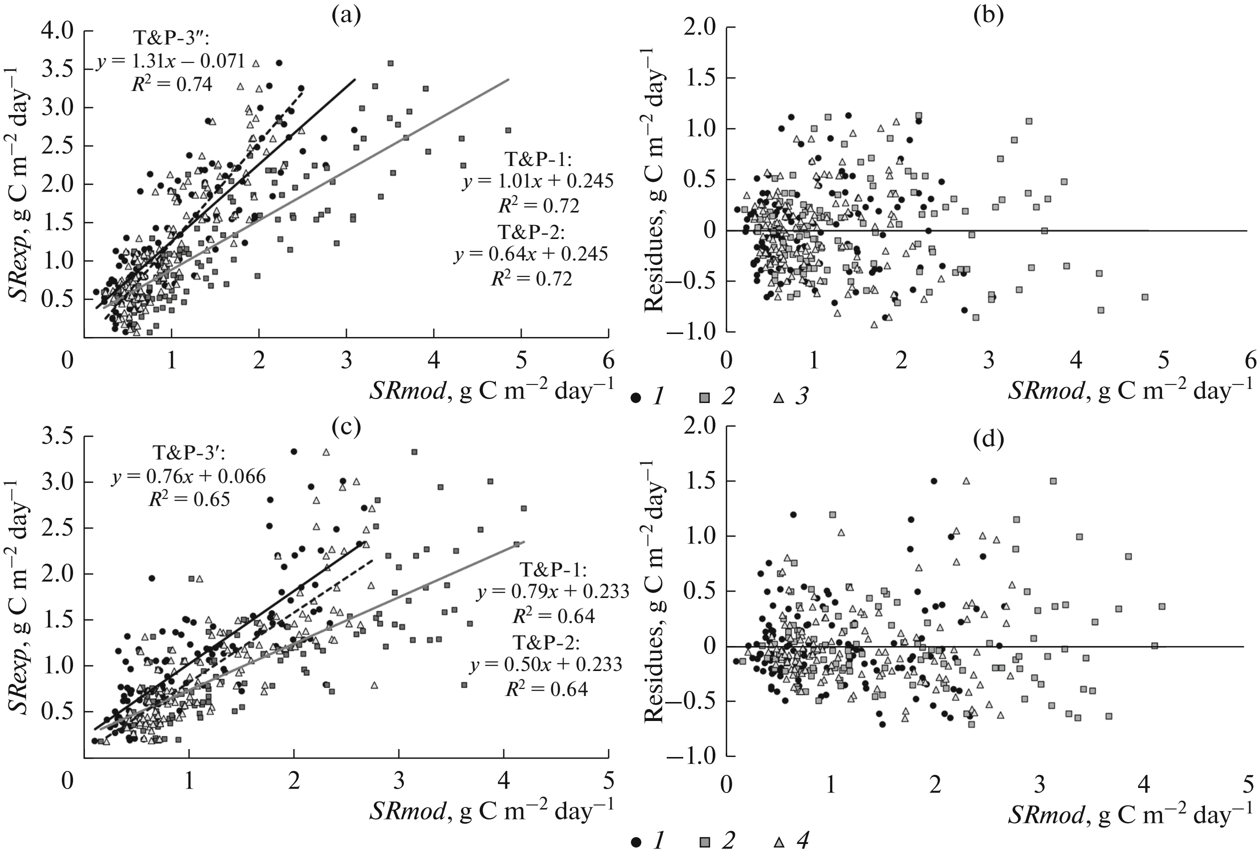

Fig. 2. Correspondence of the calculated estimates (*SRmod*) to the experimentally determined values of the mean monthly soil respiration rate (*SRexp*) and the distribution of residues, which were obtained based on different versions of the T&P model for different test samples: 1998–2007 (a, b) and 2008–2017 (c, d). (*1*) T&P-1, (*2*) T&P-2, (*3*) T&P-3″, and (*4*) T&P-3′.

have a pronounced dependence on *SRmod,* despite the high scatter of these values, which allows us to conclude that all versions of the T&P model are suitable for a numerical estimate of *SRm* based on the main climatic parameters—*Ta* and *P*.

Thus, the numerical experiments that were carried out allow us to conclude that all versions of the T&P model (initial and parameterized on the basis of training samples in different time intervals) can be successfully used to assess the long-term time dynamics of the mean monthly respiration rate of the sod-podzolic soil under the forest cover. In the study of Chinese researchers (Chen et al., 2009), the parameterized versions of the T&P model were used to estimate the spatial distribution of the annual soil respiration value using the mean annual air temperature and annual precipitation as independent variables. The authors showed the applicability of these models for all types of ecosystems (agro-, forest, and meadow ecosystems). The greatest agreement of the experimental data with model calculations was obtained for meadow cenoses (R^2 = 0.51), and the least agreement was obtained for forest ecosystems (R^2 = 0.31). The introduction of an additional parameter into the initial model, which makes it possible to take into account the carbon stocks in the soil (*T&P&C model*), significantly improved the results of modeling the annual CO_2 fluxes from soils in all types of ecosystems (Chen et al., 2010). However, it is noteworthy that in the initial versions of the T&P model proposed by Raich et al. (Raich and Potter, 1995; Raich et al., 2002) the parameter R_0, which reflects the intensity of soil respiration at mean monthly temperatures that are close to zero, indirectly depends on the supply of soil with organic matter and its bioavailability.

Accuracy of Seasonal and Annual Flux Estimates based on Mean Monthly SRm Values Determined Using Different Versions of the T&P Model and Experimental Measurements

The correspondence between the estimates of seasonal and annual CO_2 fluxes from soils that were obtained on the basis of different versions of the T&P model and the experimental data for the 20-year observation period depended on the applied version of the model, the time period for which the calculations were carried out, and the year of research (Fig. 3). The

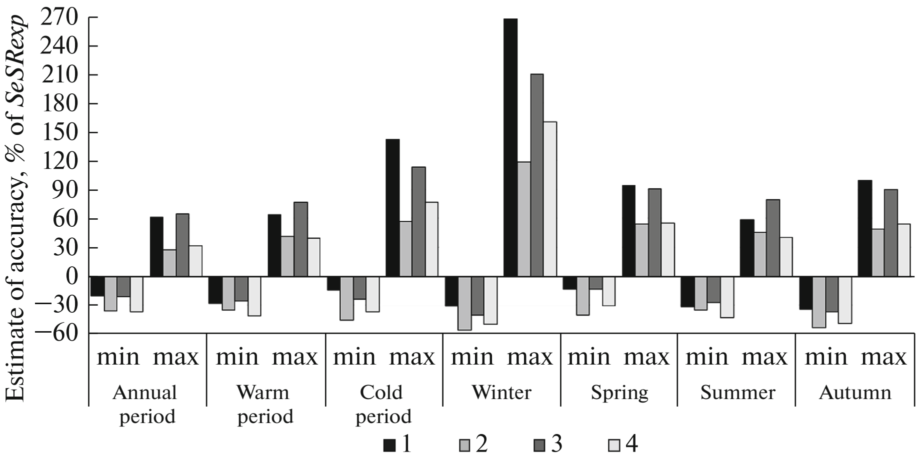

Fig. 3. Extreme discrepancies between the total calculated estimates of *SeSRmod* in different periods of the year, which were obtained using the ensemble of T&P model*s*, and the experimentally determined values of seasonal and annual CO_2 fluxes from soils (*SeSRexp*) in 1998–2017. The discrepancies are presented as the difference between *SeSRmod* and *SeSRexp* for a certain period, which is compared with the *SeSRexp* value and is expressed in %. Negative values correspond to the maximum underestimation of *SeSRexp*, while positive values correspond to the maximum overestimation of *SeSRexp*.

extreme discrepancy between the calculated data and experimental data were shown by all tested versions of the T&P model for the winter and cold periods. The overestimation of the total winter fluxes in some years could reach 142 and 267% for the cold and winter periods, respectively, and their extreme underestimation was significantly lower and amounted to 30–56% for the winter season and 14–45% for the cold period (Fig. 3). Making allowance for the low share of the winter period in the annual CO_2 flux from soils (Table 1), the noted discrepancies will not as noticeably affect the calculated values of the total annual respiration of the sod-podzolic soil as a whole. The greatest agreement of the calculated and experimental values was shown by CO_2 fluxes from soils in summer, warm, and annual periods, for which extreme discrepancies in some years were no more than 60–80%. The extreme overestimation of fluxes was usually more pronounced than their underestimation in all seasons (Fig. 3).

Our study compared the mean long-term experimentally determined values of the seasonal and annual CO_2 fluxes from soils (based on 20-year observations) and the mean long-term estimates based on different versions of the T&P model and climatic parameters for the same period (Table 4). It is shown that the accuracy of the estimates obtained using the T&P-1 and T&P-3′ versions was the lowest for the cold, winter, and spring periods: the mentioned versions of the T&P model overestimated the values of these CO_2 fluxes from soils by 40–46% and 24–17%, respectively (Table 4). In all other periods of the year, the correspondence of the long-term experimental values of *SeSRexp* to the calculated values of *SeSRmod* was rather high and the value of *PrAs* usually did not exceed 15–17%. For example, the quality of the numerical estimate of annual CO_2 fluxes from the sod-podzolic soils using all versions of the T&P model was quite satisfactory, and the deviation from the mean long-term experimentally obtained value (437 ± 21 g C m^{-2} yr^{-1}) ranged from –7 to 16% (Table 4). That is, some versions of the T&P model may overestimate *SeSRexp*, while others may underestimate it.

In addition, we compared the *SeSRexp* values with the average estimated *SeSRmod* values of the seasonal and annual CO_2 fluxes from the soil, which were obtained on the basis of the ensemble from all four versions of the T&P model and separately from only two initial versions (T&P-1 and T&P-2). The accuracy of these average estimates was almost the same (Table 4) and very optimistic. Thus, the averaged *SeSRmod* values for the total annual CO_2 flux from the soil almost completely coincided with *SeSRexp*; the *SeSRmod* values for the summer and warm seasons showed a slight underestimation, which was 1.5 and 2.9%, respectively. The most significant discrepancy between the calculated estimates and experimental data was found for the spring season (overestimation of ~16%) and autumn season (underestimation of ~10%).

Thus, we can conclude that the 20-year observation period covered the whole variety of intra-annual climatic conditions, which are different combinations of heat supply and moistening, both at the monthly level of averaging and at the seasonal and annual levels. The efficiency of all tested versions of the T&P model for assessing seasonal and annual CO_2 fluxes from the sod-podzolic soil in the years with different weather conditions could be both very low (Fig. 3) and quite high. A particularly good degree of agreement with the experimental data was demonstrated by the average estimated *SeSRmod* values of seasonal and annual CO_2 fluxes from the soil, which were obtained

Table 4. Precision assessment (***PrAs***) for different versions of the T&P model for calculating the mean long-term seasonal and annual CO_2 fluxes (*SeSRmod*, g C m^{-2}) from the sod-podzolic soil of the Prioksko-Terrasny Biosphere Reserve

Period	Parameter	Version of the T&P model				Mean*		*SeSRexp* ± CI**
		T&P-1	T&P-2	T&P-3′	T&P-3″	(1)	(2)	
Annual period	*SeSR*, g C m^{-2}	488	390	485	390	439	438	437 ± 43
	PrAs, %	**16**	**–8**	**15**	**–7**	**0.4**	**0.2**	
Warm period	*SeSR*, g C m^{-2}	333	291	348	276	312	312	321 ± 36
	PrAs, %	**9**	**–5**	**14**	**–10**	**–2.9**	**–2.9**	
Cold period	*SeSR*, g C m^{-2}	156	99	138	114	127	127	116 ± 13
	PrAs, %	**41**	**–11**	**25**	**3**	**9.4**	**8.8**	
Winter	*SeSR*, g C m^{-2}	66	40	56	47	53	52	51 ± 9
	PrAs, %	**48**	**–11**	**24**	**4**	**4.6**	**2.7**	
Spring	*SeSR*, g C m^{-2}	114	85	111	90	99	100	86 ± 10
	PrAs, %	**40**	**3**	**37**	**11**	**16.0**	**16.6**	
Summer	*SeSR*, g C m^{-2}	194	180	209	165	187	187	190 ± 24
	PrAs O, %	**8**	**–1**	**17**	**–8**	**–1.5**	**–1.5**	
Autumn	*SeSR*, g C m^{-2}	114	85	109	89	99	99	111 ± 14
	PrAs, %	**11**	**–17**	**7**	**–13**	**–10.3**	**–10.5**	

*(1) Mean value for the T&P-1 and T&P-2 versions (initial versions of the T&P-model) and (2) mean value for all four versions of the T&P model; **CI is the confidence interval of the mean.

on the basis of the ensemble from all four versions of the T&P model and separately from only two initial versions (T&P-1 and T&P-2).

The annual CO_2 flux from the soil is of the greatest demand for determining the carbon balance in all ecosystems (and in forest ecosystems in particular). Our calculations allow us to conclude that the simultaneous use of the two initial versions of the T&P model can be recommended to determine the total seasonal and annual fluxes under the conditions of a temperate continental climate, in the absence of experimentally obtained data on the determination of CO_2 emissions from soils. Conducting sequential calculations based on a 20-year series of weather data and subsequent averaging of the obtained values will make it possible to obtain expert estimates of annual and seasonal CO_2 fluxes from soils. Today, the climate data required for the T&P model are publicly available, so the calculations described above can be performed over longer time periods.

Estimate of Seasonal and Annual Fluxes Obtained from SRm Values Determined Using Different Versions of the T&P model and Averaged Climatic Parameters

Another variant of calculating the monthly soil respiration rate *(SRm-mean)* using four versions of the T&P model was performed using climatic data averaged over 20 years (1998–2017), which were used in the T&P model as independent variables. Then, on their basis, the values of the seasonal and annual CO_2 fluxes were calculated (as the arithmetic sum of *SRm-mean* for the corresponding months) and, similarly to the algorithm described above, the accuracy of the model calculations was estimated in relation to the experimentally obtained average estimates of the corresponding seasonal CO_2 fluxes from the sod-podzolic soil. The results were very encouraging (Table 5). The accuracy of the estimates of seasonal annual fluxes obtained in this way reflected all the patterns that were described in detail above, with the only difference being that the absolute *PrAs* values for the mean values for the two initial versions of the T&P model and for the ensemble from all four versions of the T&P model turned out to be slightly higher when using the mean long-term weather data. The use of the weather data averaged over 20 years in most cases overestimated the experimentally obtained seasonal and annual CO_2 fluxes from soils. Thus, the averaged *SeSRmod-mean* values for the annual, summer, and winter CO_2 fluxes from the soil were on average 4.5–6.7% higher than *SeSRexp*, and the *SeSRmod-mean* values for the warm season showed an overestimation of approximately 3% (Table 5). The most significant discrepancy between the calculated estimates and experimental data was revealed for the spring period: the overestimation was ~22%.

Table 5. Precision assessment (***PrAs***) for different versions of the T&P model when using averaged weather parameters for 1998–2017 for calculating seasonal and annual CO_2 fluxes (*SeSRmod-mean*, g C m^{-2}) from the sod-podzolic soil of the Prioksko-Terrasny Biosphere Reserve

Period	Parameter	Version of the T&P model				Mean*		*SeSRexp* ± CI**
		T&P-1	T&P-2	T&P-3′	T&P-3″	(1)	(2)	
Annual period	*SeSR*, g C m^{-2}	512	415	508	408	464	461	437 ± 43
	PrAs, %	**17.2**	**–5.0**	**16.1**	**–6.6**	**6.1**	**5.4**	
Warm period	*SeSR*, g C m^{-2}	351	313	366	291	332	330	321 ± 36
	PrAs, %	**9.4**	**–2.5**	**13.9**	**–9.5**	**3.4**	**2.8**	
Cold period	*SeSR*, g C m^{-2}	161	102	142	118	132	131	116 ± 13
	PrAs, %	**38.7**	**–11.9**	**22.0**	**1.3**	**13.4**	**12.5**	
Winter	*SeSR*, g C m^{-2}	68	40	57	48	54	53	51 ± 9
	PrAs, %	**33.7**	**–20.3**	**11.2**	**–6.3**	**6.7**	**4.6**	
Spring	*SeSR*, g C m^{-2}	119	89	116	94	104	104	86 ± 10
	PrAs, %	**39.4**	**4.2**	**35.2**	**9.5**	**21.8**	**22.1**	
Summer	*SeSR*, g C m^{-2}	205	194	221	174	200	199	190 ± 24
	PrAs, %	**8.1**	**2.2**	**16.1**	**–8.5**	**5.2**	**4.5**	
Autumn	*SeSR*, g C m^{-2}	120	91	115	93	106	105	111 ± 14
	PrAs, %	**8.1**	**–17.6**	**3.4**	**–16.0**	**–4.8**	**–5.5**	

* (1) Mean value for the T&P-1 and T&P-2 versions (initial versions of the T&P model) and (2) mean value for all four versions of the T&P model; ** CI is the confidence interval of the mean.

CONCLUSIONS

Continuous 20-year monitoring of CO_2 emissions from the sod-podzolic soil in the mixed forest of the Prioksko-Terrasny Nature Biosphere Reserve has shown a high temporal variability of soil respiration at monthly, seasonal, and annual averaging levels, which is mainly due to different combinations of heat and moisture supply. Numerical experiments have shown that all versions of the T&P model (initial and parameterized versions based on training samples in different time intervals) satisfactorily describe the long-term time dynamics of the mean monthly respiration rate of the sod-podzolic soil under forest cover (*SRm*). The parameterization of the T&P model using experimental data as training samples almost did not improve the quality of modeling monthly CO_2 fluxes from soils in any of the test intervals. The use of weather data averaged over 20 years has shown its applicability for assessing seasonal and annual CO_2 fluxes from soil. Despite the fact that the analysis of the accuracy of calculations using the T&P model relied on very detailed experimental data obtained for only one ecosystem, we could recommend the above-described calculation methods for obtaining expert estimates of seasonal and annual CO_2 fluxes from soils in the zone of temperate continental climate, where the air temperature and the amount of precipitation determine the intra-annual intensity of soil respiration. Considering that today more and more new databases of climatic data of different and often quite detailed spatial resolution (for example, WorldClim, www.worldclim.org) are becoming available, the algorithms for assessing soil respiration using several versions of the T&P model that are presented in our work will become increasingly relevant for assessing the emission component of the carbon cycle in various regions.

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COMPLIANCE WITH ETHICAL STANDARDS

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

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

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