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A SYSTEM FOR HETEROTROPHIC SOIL RESPIRATION ASSESSMENT OF RUSSIAN LAND

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A model cluster for soil respiration assessment was developed. It is based on 3592 in-situ measurements and considered climatic parameters, soil and vegetation types, land use, vegetation productivity and disturbances. Heterotrophic efflux from Russian soil was assessed as 3.47 Pg C year^{-1} or 215 g C m^{-2} year^{-1}.

Soil respiration (SR) is one of the most important and least understood components of the global carbon cycle. Recent global estimates suggest that soil emits about 98 Pg C per year, which exceeds emission rates from fossil fuel combustion by an order of magnitude [3, 6]. While indicating that soils are the predominant source of CO_2 from terrestrial ecosystems, such estimates are still highly uncertain [1].

The vast territory of Northern Eurasia has accumulated large amounts of organic carbon in the soil over centuries. The uncertainty of its behavior in light of rising temperatures is cause for concern. Rising temperatures could lead to increasing rates of respiration, potentially creating a positive feedback. We therefore consider it of utmost importance to, with the use of in-situ measurements; build a spatially explicit model cluster to identify soil respiration climatic drivers over this large region.

SR measurement is a laborious process. That is why only a limited amount of data is available. SR varies substantially depending upon a number of reasons besides of climate. We assumed that there is a climate dependence of SR, which transforms in certain soil conditions under certain vegetation and disturbances. SR estimation was carried out by the following steps.

1. Build total SR regression models depending on climate parameters within soil groups. We have used our soil respiration database, which contain about 3592 records from 1109 studies over the globe.
2. Provide model modification for individual biome, vegetation type and disturbances. We calculated a correction coefficient, which corresponds to the relation of mean measured SR to the model SR estimation for each biome, vegetation type and disturbances.
3. Build a model of autotrophic respiration (contribution of roots) share in total SR depending on biome and vegetation type.
4. SR correction depends on the current level of Net Primary Production (NPP).

All available studies on soil respiration measurements *in situ* that were reported in peer-reviewed scientific literature were collected in a database. The main part of the data was taken from the global database by Bond-Lamberty and Thomson [4]. These authors have collected about 3379 records from 818 studies. We found about 291 more sources mostly for the northern hemisphere, especially Russia. Totally about 1109 studies were used and 3592 records on soil respiration fluxes around the world were collected, spanning the measurement years 1961-2008.

Climate data (temperature and precipitation) for the period 1974 – 2005 were obtained from FOODSEC [7]. FOODSEC receives daily, 10-daily and monthly outputs of the ECMWF (European Centre for Medium-Range Weather Forecast) global circulation model and provides the data aggregated for 10-days periods. The original global data are at a 0.25 degree resolution. The data is provided by the ERA40 historical reanalysis time series project at 0.5 degree resolution. We use climatic data for the year of SR measurement.

Soil respiration model depends on climate parameters

We divided the SR database on soil groups according to their common genesis and features and provided regression analysis. Table 1 contains SR regression models depending on climate parameters for different soil groups.

It was found that in arctic tundra soils the carbon dioxide efflux is mostly driven by precipitation and the length of periods with temperature above 0 and 5 °C. Gleyezem respiration also depends on precipitation and hydrothermal conditions during the frost-free period and total annual precipitation. Well drained podzol soils show direct dependence of soil respiration on mean annual temperature. Other climatic drivers for this soil are duration of frost-free period plus precipitation and hydrothermal conditions during the warmest period of the year. The cold and mostly permafrost podbur SR is positively dependent on precipitation during the warmest period and negatively on that during the whole period with temperature above 0 °C. Respiration of texture-differentiated soils depends on the accumulated temperatures during the warmest period and the frost-free period as a whole. Peaty soils carbon dioxide efflux is mostly influenced by precipitation during the warmest period during a year. For peat soils the strongest drivers of soil respiration were duration of the warmest period and accumulated temperatures during the period with temperatures above 0 °C. Metamorphic soils have eight climatic drivers and the most important periods for the SR are the period with temperature above 0 °C (precipitation, accumulated temperatures and hydro-thermal conditions) and above 10 °C (duration of the period and the GTK). Respiration of sod-organic accumulative soils positively depends on mean annual temperature, and negatively reacts to the duration of the warmest period, amount of precipitation during the frost free period and moisture conditions during a growing season. The respiration of humic-accumulative soils depends on the length and precipitation of periods with temperature above 0 and 5 °C. Respiration of volcanic soils depend linearly on the conditions during the period with temperature above 5 °C. Alluvial soil respiration is influenced by mean annual temperature and precipitation amount, duration of growing season and hydrothermal conditions during the warm period of the year. Respiration of low-humic accumulative-calcareous soil linearly depends on precipitation during the period with temperature above 5 °C. At the same time including of other climatic variables gives a stronger correlation with soil respiration variation for these soils. Respiration of shallow weakly developed soils depends most on the duration of the frost free period, precipitation and accumulated temperatures at the warm period during a growing season. Sod mountain soils are mostly derived by duration of frost free season and accumulated temperatures above 5 °C.

Thus, soil respiration flux is closely dependent on climate, but soil properties are a very important factor influencing the rate of carbon dioxide release from soils.

Table 1. Models of soil respiration flux from different soil groups

Soil group	N	R^2	p-level	Model
Arctic tundra soils	23	0.71	<0.01	LnSR = 11.078+8.214*ln(D_0)-7.619*ln(D_5) -10.101*ln(P_0)+8.675*ln(P_5)
Gleyzems (overwetted soils with gley horizon)	138	0.64	<0.01	LnSR = -13.562+2.155*GTK_0-1.103*IndW +3.269*ln(MAP)-2.422*ln(P_5)+9.710*ln(IndW)
Podzol (sandy soils with light podzolic horizon)	327 327	0.42 0.40	<0.01 <0.01	LnSR = 5.687+0.144*MAT-0.00357*MAT^2 LnSR = -3.136+1.508*ln(D_0)+0.223*ln(P_10)-0.305*ln(GTK_10)
Podbur (soils with Al, Fe and humus relocation, without podzolic horizon)	46	0.29	<0.01	LnSR = 5.766+0.006*(P_10)-0.0027*(P_0)
Texture- differentiated soils (clay relocation)	454	0.45	<0.01	LnSR = 5.018+0.0011*(SUM_T_0)-0.00088*(SUM_T_10)
Peaty soils	52	0.32	<0.01	SR = -1803.79+434.93*ln(P_10)
Peat bog soils	237	0.25	<0.01	SR = 385.252-4.601*(D_10)+0.245*(SUM_T_0)
Metamorphic soils (Fe accumulation without its relocation)	462	0.25	<0.05	LnSR = 7.935-2.527*ln(SUM_T_0)-0.0291*(D_10) +0.0015*(SUM_T_5)+2.284*ln(GTK_0)-0.001*(P_0) -0.311*ln(GTK_10)+3.330*ln(D_10)+0.765*ln(IndW)
Sod-organic accumulative soils	18	0.81	<0.01	LnSR = 14.018+0.649*MAT-0.0277*(D_10)-0.0056*(P_0)-0.932*(IndW)
Humic accumulative soils	237	0.33	<0.01	LnSR = -9.852-0.0101*(D_5)-0.0042*(P_0)+0.0036*(P_5) +2.375*ln(D_0)+1.825*ln(P_5)-0.889*ln(P_10)
Volcanic soil	98	0.48	<0.01	SR = -652.208+8.068*(D_5)-0.549*(P_5)
Alluvial soils	41	0.91	<0.01	LnSR = 15.655+0.618*MAT+0.0021*MAP-0.0284*(D_0) -0.0016*(SUM_T_5)+1.809*(GTK_5)-3.287*(GTK_10)
Low-humic accumulative calcareous soils	60 60	0.78 0.83	<0.01 <0.05	SR = -322.17+2.170*(P_5)+6.155*(D_0)-4.968*(D_5)-1.501*(P_0)
Shallow weakly developed soils	139	0.51	<0.05	LnSR = -144.626-0.002*MAP-0.113*(D_0)+0.002*(P_5) +29.894*ln(D_0)+7.212*ln(SUM_5)-5.458*ln(SUM_10)
Sod mountain soils	11	0.95	<0.01	LnSR = -38.169-0.0528*(D_0)+7.311*ln(SUM_T_5)

LnSR – natural logarithm of soil respiration; D_0, D_5, D_10 – number of days with daily average temperature above 0, 5 and 10 °C; P0, P_5, P_10 – sum of precipitation when the daily average temperature above 0, 5, 10 °C, mm; SUM_T_0, SUM_T_5, SUM_T_10 – sum of degree days with daily average temperature above 0, 5, 10 °C; Prec – Annual precipitation, mm; IndW – wetness index (SUM_T_5 / Prec); GTK_0 – Hydro-thermal coefficient (P_0 * 10 / SUM_T_0).

Corrections for biome, vegetation type and disturbances

Soil respiration is a complex ecosystem process interacting with both biotic and abiotic factors. It mainly refers to the release of CO_2 from soils due to the production of CO_2 by roots and soil organisms, whose type, abundance, and production are directly related to any disturbance including land-use and management practices [11,12].

It is well known that soil microbial activities, population and communities' structure are managed by soil type and texture, temperature, moisture, pH [5], and soil management practices and crop rotation [13].

Some soils are widely-spread (alluvial for instance) and we applied corrections for certain biomes (tundra, sparse and northern taiga, middle taiga, southern taiga, temperate forest, steppe, semi-desert). The correction implies relation of average measured SR ($R^{measured}$) to model SR for a certain biome.

$$C_i = \frac{\overline{R}_{Si}^{measured}}{\overline{R}_{Si}^{\mathrm{mod}}} \tag{1}$$

The same approach was used to calculate corrections for the vegetation type (forest, shrubs, grassland, wetland) and land use/disturbances (arable, pasture, fire).

Root contribution to soil respiration

Carbon dioxide efflux from the soil has two sources: microbial respiration and plant root respiration. The partitioning of soil CO_2 efflux helps to improve our understanding of the environmental changes that drive carbon cycling [2, 9] and to accurately estimate carbon budgets of ecosystems and turnover rates of soil organic matter [15].

As far as root respiration is attributed to the plant physiological functions, it seems reasonable that this flux is dependent on vegetation type and plant growth activity.

The main climatic factors driving root contribution to the soil respiration flux in the coniferous forests are mean annual precipitation and precipitation separately during a period with mean daily temperatures above 5 and 10 °C, and hydro-thermal conditions during these periods, as well duration of the period with temperature above 5 °C and moisture conditions at the site (Table 2).

Table 2. Climatic drivers of root contribution in different vegetation classes

Vegetation	N	R^2	p-level	Model
Coniferous forest	177	0.35	<0.01	RC = 213.507+0.0656*MAP+0.120*(P_5) -0.146*(P_10)-61.452*(GTK_5)+47.921*(GTK_10) +15.141*(IndW)-51.691*ln(D_5)+46.944*ln(GTK_5) -20.802*ln(GTK_10)
Deciduous forest	86	0.22	<0.05	RC = -408.392-0.070*(SUM_T_5)+0.047*(Sum_T_10) +98.140*ln(P_5)-29.509*ln(P_10)+81.471*ln(IndW)
Grasslands	38	0.76	<0.01	LnRC = 6.999-0.629*MAT+0.0121*MAP +0.0265*(D_5)+0.0032*(SUM_T_5)+0.0134*(P_0) -0.0308*(P_5)-12.4813*(GTK_0)+16.194*(GTK_5) +7.353*ln(P_0)-12.617*ln(P_5)+1.978*ln(P_10)
Arable	47	0.58	<0.05	RC = 966.669-0.14*MAP+0.456*(P_0)-0.344*(P_5) +0.160*(P_10)-166.045*(GTK_10)-184.234*ln(P_0) +49.217*ln(P_10)+280.158*ln(P_5)

Deciduous forests root contribution depends on accumulated temperatures during a period with temperature above 5 and 10 °C, and amount of precipitation during these periods. Root contribution of grasslands vegetation depends mostly on periods with temperature above 0 and 5 °C. Root contribution of agricultural plants is derived by precipitation during a different period of the year.

Correction to the current level of ecosystem production

Soil respiration depends also on the available source of organic matter. At the final stage we adjusted the SR value for each certain point of territory depending on NPP.

$$HR = NPP \frac{\sum HR_{S,E}}{\sum NPP_{S,E}} \tag{2}$$

where HR – heterotrophic respiration; NPP – net primary production; $\Sigma HR_{S,E}$, $\Sigma NPP_{S,E}$ – sum of HR and NPP for a certain soil and forest enterprise.

The equation (2) doesn't change total carbon efflux for a forest enterprise, just redistributes a value depending on NPP.

Results and Discussion

Climate is the main driver of soil respiration. It controls both autotrophic respiration flux and microbial activity. Soil also shows its importance in SR estimation. It transforms climate parameters and reflects other factors (parent material, relief etc.). Soil features can affect both root respiration and heterotrophic activity by providing favorable or unfavorable conditions for root development and organic matter decomposition. However, different vegetation types on a similar soil can provide another autotrophic respiration flux and input of organic substances into the soil. Natural disturbance and anthropogenic activity can lead to the shift of vegetation cover on the soil. That in turn can lead to the changes in respiration flux.

Heterotrophic respiration flux from Russian soil was assessed as 3.47 Pg C year^{-1}. Average HR by zone and vegetation type is presented in the Table 3.

Table 3. Distribution of average heterotrophic soil respiration by zone and land use

Biome	Heterotrophic Respiration, g C m^{-2} year^{-1} by land use							
	forest	sparse forest	burnt area	arable	other agro	wetland	grassland, shrubs	average
Arctic							54	54
Tundra	155	99	95	128	158	101	109	99
Northern taiga	151	115	106	182	244	187	157	153
Middle taiga	192	124	172	323	310	259	264	204
Southern taiga	288	317	390	351	350	398	481	315
Moderate forest	365	337	297	293	355	493	455	358
Steppe	323	428	380	377	327	641	537	373
Semi desert	313	382	241	232	218	390	261	238
Average	210	136	164	360	317	220	194	215

Table 4 contains comparison of different SR assessments.

Table 4. Comparison of SR assessments

HR total, Pg C год$^{-1}$	HR average, g C m^{-2} год$^{-1}$	Relation to our estimation, %	Reference
3.20	196	92	Nilsson et al., 2000 [10]
2.78	171	80	Kurganova, 2003 [8]; Zavarzin, Kudeyarov, 2003 [16]
3.47	215	100	our current estimation

Our estimation of HR is higher than others, but is based on the most representative in-situ measurements database and corresponds to the latest assessment of net primary production [14].

The main advantages of the method are the following:

- All available in-situ measurements were used to build the model.
- The model can be implemented for a changing climate.
- It considered soil and vegetation type, land use and disturbances along with climate parameters.
- The model can be adjusted in an automated way when new measured SR data have been received.

Our result is presented in a form of SR map with 1 km spatial resolution. More information can be found at http://www.iiasa.ac.at/Research/FOR/hlc/

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