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GEOCHEMISTRY

Carbon Budgets in the Steppe Ecosystems of Russia

I. N. Kurganova[a,*], V. O. Lopes de Gerenyu[a], A. T. Zhiengaliyev[b], and Corresponding Member of the RAS V. N. Kudeyarov[a]

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Abstract—Abandoned lands formed in the place of former arable lands occupy considerable areas in the steppe zone and are a basic reserve for the restoration of the steppe biome in Russia. Taking into account the secondary steppe ecosystems developed in the place of the abandoned lands, the total carbon dioxide sink in the steppe zone of Russia can reach 92–121 Mt C per year. This is comparable to the CO_2 sink in the managed forests of the Russian Federarion (96 Mt/yr) and accounts for 10–20% of the total sink of CO_2 in the terrestrial ecosystems of Russia. To increase the sink potential on the territory of the Russian Federation, the natural and restored steppe ecosystems should be preserved.

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The cycle of organic carbon (C) is the main biogeochemical cycle on our planet [3]. Its production component is determined by carbon assimilation in the photosynthesis process and is expressed by the amount of net primary production (NPP) formed during the year. The destruction component of this cycle integrates the whole diversity of the processes of decomposition of organic materials (soil, litter, and woody debris) and is usually represented by a total microbial respiration flux (MR). The imbalance between the production and destruction of organic carbon determines the amount of organic carbon that is released from the carbon cycle, deposited in the soil, and manifested in the change in the concentration of carbon dioxide in the atmosphere. Thus, through the greenhouse effect, the biogenic cycle of carbon is related to the problem of global climate change, one of the most important ecological problems today.

The current balance of carbon for the territory of Russia is estimated in the range of 0.5–1.0 Gt C/yr; i.e., our country acts as an absolute sink of carbon dioxide from the atmosphere, and its terrestrial ecosystems provide for at least 1/5 of the global CO_2 sink [4]. The role of the steppe biome in the biogenic carbon cycle has been the least defined on the territory of Russia, that is likely explained by the relatively small share of virgin steppe preserved in our country. Since the most fertile soils (Chernozems and Chestnut soils) are formed under steppe vegetation, huge steppe areas, except for desertified areas, have been cultivated, and the unplowed areas were used as pastures and hay fields. Today, the area of the natural steppe ecosystems on the territory of the Russian Federation is estimated at 34–50 mln ha [13, 15], which is ~21–30% of the total area of steppe zone. At the same time, there is the most extensive steppe zone in the world in the territory of Northern Eurasia that extends as a continuous band from Hungary to Transbaikal [5, 9]. Occupying an area of 800 mln ha [2], the Eurasian steppes, their state and use can significantly affect the global carbon budget. As part of this research, we estimated the main components of the carbon balance in the natural steppe ecosystems and determined the role of steppes in the current budget of carbon for the territory of Russia.

The production component of the carbon cycle in the natural steppe biomes was determined from the database based on the experimental determination of NPP, including 63 records [1, 2, 7, 8]. All steppe ecosystems were referred to one of the following subtypes [5]: meadow, true, arid, dry, and desertified (Table 1). It was found that depending on the subtype, NPP in the steppe ecosystems varies from 813 ± 99 g C/(m^2 yr) in the zone of meadow steppes to 328 ± 44 g C/(m^2 yr) in the desertified ones. The average value of NPP for the steppe ecosystems in Russia is 640 ± 29 g C/(m^2 yr), which exceeds the average value of NPP 319 ± 19 g C/(m^2 yr) on the forest-covered lands in the Russian Federation by a factor of 2 [10].

The CO_2 emission from soils of virgin steppe (or the total soil respiration, TSR) was determined regulary in only 19 ecosystems and during the summer (or vegetation) period in most cases (Table 2). The esti-

[a] *Institute of Physicochemical and Biological Problems in Soil Science, Russian Academy of Sciences, Pushchino, Moscow oblast, 142290 Russia*
[b] *Zhangir Khan West Kazakhstan Agrarian-Technical University, Uralsk, Kazakhstan*
**e-mail: ikurg@mail.ru*

Table 1. Net primary production (NPP, g C/(m^2 yr)) in the different subtypes of the steppe ecosystems

Parameter	All steppes	Subtype of steppe ecosystems				
		meadow	true	arid	dry	desertified
Number of ecosystems	63	17	16	8	15	7
Average	640	813	703	608	541	328
Median	632	812	746	592	542	256
Minimum	209	502	372	264	263	209
Maximum	1058	1058	996	916	1010	485
Standard deviation (STD)	226	162	167	216	194	117
Standard error (SE)	29	39	42	76	50	44
Coefficient of variation (CV), %	35	20	24	35	36	36

mates of the annual CO_2 fluxes from the steppe soils based on the published data and the model which was developed earlier [13] indicate their very strong variability: from 194 to 3269 g C/(m^2 yr). Such high dispersion of the annual CO_2 fluxes from soils of virgin steppe is primarily related to the great diversity of soil and vegetation cover of the steppe, the difference in weather conditions in particular years of the studies, the difference in the measurement frequency and duration, as well as the differences in the methods used for measuring TSR. The average annual CO_2 flux from soils of the steppe cenoses is estimated at 869 ± 174 g C/(m^2 yr), and the coefficient of variability is high and amounts to 87% (Table 2).

Based on our earlier analysis of the database on the contribution of roots to the total CO_2 flux from the soils [13], we revealed that, in the meadow and grassland ecosystems, the shares of the root respiration (RR) and microbial respiration (MR) components in TSR are 45 and 55%, respectively. Thus, the average MR value in the soils of the virgin steppe is 478 ± 95 g C/(m^2 yr) (Table 2), and the average value of the carbon balance, representing the difference between NPP and MR (Net Ecosystem Production, NEP = NPP – MR), equals 162 ± 99 g C/(m^2 yr). The obtained estimate of CO_2 sink in the steppe ecosystems of Russia exceeds the average value of the carbon dioxide sink on the Russian lands covered by forests by approximately a factor of 2.5: 66 ± 15 g C/(m^2 yr) [10], demonstrating a high sink potential of the virgin steppe.

Table 2. Total and microbial soil respiration in the steppe ecosystems (g C/(m^2 yr))

Parameter	Total soil respiration (TSR)		Microbial respiration (MR, annual)
	summer	annual	
Number of ecosystems	17	19	19
Average	491	869	478
Median	301	516	284
Minimum	112	194	107
Maximum	1372	3269	1798
Standard deviation (STD)	377	757	416
Standard error (SE)	91	174	95
Coefficient of variation (CV), %	77	87	87

The direct estimations of the NEP value in the virgin steppe of Khakassia (the south of Krasnoyarsk krai) made using the micrometeorological method showed that the natural steppe ecosystem absorbs 152 ± 37 g C/m^2 of carbon during the vegetation season. The abandoned lands formed in the former arable Chernozems in the steppe zone of Khakassia also act as an absolute sink of carbon dioxide with the NEP value equal to 114–201 g C/m^2 during the vegetation season [11]. And although, beyond the vegetation, the steppe ecosystems are a source of CO_2 into the atmosphere due to microbial soil respiration, its value is significantly lower than the amount of C absorbed by virgin soils during the vegetation season [13]. The direct estimations of the carbon balance performed in the steppe ecosystems of Kazakhstan that similar to the Siberian steppe regions in their formation conditions showed that they are also sinks of atmospheric CO_2 with similar NEP values: from 43 to 173 g C/(m^2 yr) (Table 3). In Western Europe, the grasslands and meadow ecosystems can act both as a large sink (>653 g C/(m^2 yr)) and as a source of CO_2, with the NEP value = –164 g C/(m^2 yr). In the American prairies, the variability in NEP values was also quite significant, from 344 g C/(m^2 yr) (sink) to –173 g C/(m^2 yr) (source) depending on the different factors: climatic, the presence of grazing or spring fires. Thus, the direct estimation of the ability of steppe ecosystems to absorb carbon dioxide by the

Table 3. Estimation of carbon balance (NEP, g C/(m^2 yr)) in the steppe ecosystems of the world's different regions based on direct determination using the micrometeorological method (the negative NEP values are CO_2 sources, the positive NEP values are sinks)

Region of the World	Virgin soil /deposits	Grassland/grazing
Russia* [11]	151±37/146–201	
Kazakhstan [14]	42–173	–4–146
European countries [11, 14]	–173–653	
North America [11, 14]	–146–109	–69...+141

* g C/ m^2 over the vegetation period.

eddy covariance method showed that the NEP value in the natural steppe ecosystems strongly varies, and to evaluate the role of steppes in the carbon budget of Russia more reliable, the network and duration of such observations should be extended.

Taking into account the area occupied by steppe ecosystems (34–50 mln ha) and the difference in the specific NEP estimations obtained by the direct and difference methods, the total absorption of carbon dioxide in the steppe regions of the Russian Federation can be estimated from 52 ± 13 to 81 ± 50 Mt C/yr. As a result of abandoning the former agricultural lands caused by the economic crisis in the early 1900s, 26 mln ha of former croplands were removed from agriculture in the steppe zone, and now the secondary (restored) steppes have been formed there [6]. The abandoned ecosystems in the steppe zone also represent a stable carbon sink [11, 14] with a value equal to 114–201 g C/(m^2 yr) (Table 3). Taking into account the areas of the restored steppe ecosystems, the total carbon dioxide sink in steppe zone can reach 92–121 Mt C per year, which is comparable to the carbon sink in the managed forests of the Russian Federation (96 Mt/yr), and amounts to ~15% of the total up-to-date carbon sink for all forest lands of Russia, 546 ± 120 Mt C/yr [10]. According to the approximate estimations, the virgin steppe ecosystems and abandoned lands formed in the zone of steppes in the place of the former arable land can provide for 10–20% of the total sink of CO_2 to the terrestrial ecosystems of Russia, which is a rather significant part of the annual carbon budget in the territory of our country. Taking into account the strong sink potential of the virgin and restored steppes, it is necessary to preserve and use them more rationally, being guided by the priorities created by nature itself, viz., moderate grazing [9] and the use of soil-saving technologies in plant production.

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