Estimation of C-CO$_2$ balance of natural steppe ecosystems: Khakassia and Tuva (Eastern Siberia, Russia) case studies

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Abstract. The study of carbon balance of terrestrial ecosystems is considerable important for the forecasts of climate and environmental changes. Using a geoinformation-analytical method and a climate-driven regression model, we have calculated the C–CO$_2$ balance of natural steppe ecosystems of Khakassia and Tuva. Our research has shown that natural steppes of the region under study are a significant sink of carbon dioxide from the atmosphere. The intensity of this carbon flux in the region can be estimate as 184±41 gCm$^{-2}$yr$^{-1}$. The annual absorption of carbon dioxide in the natural steppe ecosystems of Tuva and Khakassia is evaluated as 6.9±2.2 Mt C–CO$_2$.

1. Introduction
The terrestrial carbon cycle is an important component in study of climate change impact on natural vegetation and vegetation feedback on climate [1, 2, 3]. Net primary production and soil heterotrophic respiration are the major fluxes in the terrestrial carbon cycle [4, 5, 6]. Net primary production, one of the key characteristics of the plant cover, is determined as the amount of organic matter accumulated in a plant community per unit area during a certain time period (usually, a year). Soil heterotrophic organisms decompose organic matter in soil and produce carbon dioxide that is released into the atmosphere. Net primary production and soil heterotrophic respiration exert an essential effect on carbon balance in terrestrial ecosystems [7, 8, 9]. The intensity of these carbon fluxes varies in different plant biomes. The imbalance between the production and destruction of organic carbon in the terrestrial ecosystems can lead to significant changes in the concentration of carbon dioxide in the atmosphere with consequent feedbacks to climate change [10, 11]. Today the study of carbon balance for terrestrial ecosystems is a key task for forecasts of climate and environmental changes.

Steppes are arid grassland ecosystems. In Eurasia the territory with steppe ecosystems is a vast territory with area approximately $8\times10^6$ km$^2$ that is stretched from Hungary to Transbaikalia and located between 45$^\circ$ N and 58$^\circ$ N. The width of the steppe zone varies from 150 km to 400 km at the west an east confines of steppe belt and reaches about 600 km in the central part (Western Siberia, Kazakhstan) [12, 13]. Climate in the steppe regions ranges from temperate semi-arid to sharply continental. Variability of climatic characteristics determines the zonality and contrast of the soil cover and vegetation in steppe ecosystems [12]. The steppe vegetation have the powerful rootage: the share of the belowground organs in the total plant phytomass is about 90% [14, 15]. Currently the carbon fluxes, stocks of soil organic carbon in grassland ecosystems, and the role of the steppe zone in the terrestrial carbon cycle are not well known or understood.

The aim of this study is to evaluate the C–CO$_2$ balance in the natural steppe ecosystems in the Republic of Khakassia and the Republic of Tuva.

2. Materials and methods
The Republic of Tuva (area – 168.6×10$^3$ km$^2$, capital – Kyzyl) and the Republic of Khakassia (area – 61.6×10$^3$ km$^2$, capital – Abakan) are located in the southern path of Eastern Siberia (Russia) (figure 1).
Tuva and Khakassia are the mountainous regions with alternating mountain ranges and intermontane depressions. The steppe ecosystems occupy the intermontane depressions in these republics. There are true and dry steppes in Khakassia. In Tuva Republic, meadow, true, dry and desert steppes are observed. Most of the steppes in the republics are plowed and used as pastures and hayfields [16].

Climate in Khakassia and Tuva is sharply continental. However climate in the depressions of Khakassia is quite warm: mean annual temperature is positive (~0.9°C). The growing period lasts from mid-April to mid-October. The snow cover is insignificant. The average annual rainfall is 350–500 mm. The depressions in Tuva are characterized by inclement climate: winters are very cold, summers are hot. Mean annual temperature ranges from −5.7°C to −3.0°C. The growing period lasts from May to September. The average annual precipitation varies from 180 mm to 400 mm in the depressions [16, 17].

Estimation of net primary production (NPP) for the steppe ecosystems in the studied regions was obtained on the basis of a geoinformation-analytical method. For calculations we have used a database of empirically obtained NPP values [14–21]. For true steppes in Khakassia the NPP values range from 1310 to 2150 gm $^{-2}$ per year with an average of 1990 gm $^{-2}$yr $^{-1}$. It should be noted that the share of the belowground organs in the total NPP for steppe plants is about 85% [15, 18]. The NPP values for true steppes in Tuva are comparable with those in Khakassia. In the studied regions the productivity of dry steppes changes from 580 to 2040 gm $^{-2}$ per year (average NPP value is 1410 gm $^{-2}$yr $^{-1}$). The desert steppes in Tuva are characterized by low productivity which varies from 550 to 1400 gm $^{-2}$ per year (average NPP value is 1030 gm $^{-2}$yr $^{-1}$). The NPP values for meadow steppes was the highest and amounts to 2010–2560 gm $^{-2}$ per year. Using specific carbon concentrations for different steppe ecosystems [22] we have expressed the empirical data for NPP in the carbon units.

There are very few experimental data on the CO$_2$ emissions from soils (soil respiration, SR) for natural steppe ecosystems. To estimate the soil respiration in certain regions, a climate-driven regression mode (T&P model) [23] can be used. The model allows us to estimate the mean monthly CO$_2$ efflux rate from soil (SR in gCm $^{-2}$d $^{-1}$) based on the mean monthly air temperature and monthly amount of rainfall according to the following equation:

$$SR = R_0 \exp(QT) \frac{P}{K + P}$$

where $T$ is mean monthly air temperature (°C), $P$ is the monthly precipitation (cm). The model contains three parameters: $R_0$ (gCm $^{-2}$d $^{-1}$) represents the soil respiration rate when the mean monthly air temperature is 0°C, $Q$ (°C$^{-1}$) defines the rate of change of the soil respiration rate with respect to temperature, and $K$ (cm⋅month$^{-1}$) is the half-saturation constant for a hyperbolic relationship between soil respiration and rainfall.

Due to the lack of experimental data on CO$_2$ emissions from soils in steppe ecosystems, we have used experimental data obtained for two meadow ecosystems in the Moscow region for the parameterization of the T&P model (1). The used experimental data included meteorological parameters and values of the weekly soil respiration for 20-year and 14-year monitoring in the two grassland sites. One of them was located on the Retisol (sandy), the other – on the Luvic Phaeozem (loamy). With some assumptions, these grasslands can be considered as ecosystems close to meadow steppe. Using the experimental data for two meadow ecosystems, we have calculated parameters (2 collections) for the T&P model. The numeric experiments showed that these versions of T&P model satisfactorily describe the interannual dynamics of mean monthly soil respiration [24]. In our study we have used the mean value of the monthly SR values based on the ensemble of two versions of the T&P model to evaluate the annual CO$_2$ effluxes from soils in the steppe ecosystems.

Monthly air temperatures and precipitation data for our study were obtained from the WorldClim database (www.worldclim.org), which used meteorological observations for 1970–2000.

Soil respiration represents the combined respiration of living roots and associated rhizosphere (autotrophic respiration, AR) and respiration of soil micro and macro-organisms (heterotrophic respiration, HR). Soil micro and macro-organisms decompose the dead organic matter in litter and
soil. It was found that AR contribution to the total SR varies over a very wide range from 6% to 95% [25, 26] and depends on the type of vegetation and time of investigation. We revealed [26] that the shares of the AR and HR components in soil respiration for grassland ecosystems amount to 45% and 55% respectively.

![Figure 1. Steppe sub-zones in Tuva and Khakassia Republics: 1 – meadow steppes, 2 – true steppes, 3 – dry steppes, 4 – desert steppes.](image)

The net ecosystem production (NEP) determines the function of any terrestrial ecosystem as source or sink of carbon. The NEP value is defined as the difference between carbon income into the net primary production formed in the ecosystem and its emission from dead organic matter:

$$NEP = NPP - HR$$  \hspace{1cm} (2)
If net ecosystem production (2) for a given ecosystem is positive value, then carbon release into the atmosphere is smaller than its absorption and an ecosystem serves as sink of carbon. In contrast, if NEP for a given ecosystem is negative value, then carbon release into the atmosphere is higher than its absorption and this ecosystem is a source of carbon.

3. Results and discussion
Natural steppe ecosystems occupy about $7.0 \times 10^3$ km$^2$ in Khakassia and $27.6 \times 10^3$ km$^2$ in Tuva [27]. In 1975–1990 most of the steppe zone in Tuva and Khakassia are used in agriculture as arable land, pastures and hayfields. As a result of the economic crisis in the early 1990s, large areas of the agricultural lands were abandoned in steppe zone of Tuva and Khakassia. Steppe vegetation has restored on former croplands and pastures over the last two-three decades. Now secondary (restored) steppes have formed on abandoned lands. Using database of Federal Service for State Registration, Cadastre and Cartography (www.rosreestr.ru), we have estimated areas for restored steppes. According to our calculations, restored steppes occupy about $6.8 \times 10^3$ km$^2$ in Khakassia and $26.1 \times 10^3$ km$^2$ in Tuva. The area distributions of nature and restored steppes in the regions under study was shown in Figure 2. In the present study, we referred restored steppes to natural steppes.

![Figure 2](image.jpg)

**Figure 2.** The area distributions of nature and restored steppes in Tuva and Khakassia Republics.

Using the geoinformation-analytical method we have estimated the mean annual biological productivity of the natural steppe ecosystems in Tuva and Khakassia. Our calculations have shown that the natural steppe ecosystems accumulate $9.0 \pm 0.9$ Mt C–CO$_2$ and $18.3 \pm 2.4$ Mt C–CO$_2$ per year in Khakassia and Tuva respectively. The average NPP values amount to $654 \pm 62$ gCm$^{-2}$yr$^{-1}$ and $341 \pm 49$ gCm$^{-2}$yr$^{-1}$ for these regions respectively.
In our study we applied two versions of the T&P model to estimate the mean monthly soil respiration based on the mean monthly climate data (air temperature and precipitation). Using experimental data for the meadow ecosystems, we have calculated following parameters for first version as $R_i=1.687$, $Q=0.0569$, $K=2.203$ and for second version as $R_i=1.843$, $Q=0.0654$, $K=2.745$. Based on the both T&P-model versions, we have found that the C–CO$_2$ effluxes from soils of the steppe ecosystems in Tuva and Khakassia amount to 373±21 gCm$^{-2}$yr$^{-1}$ and 514±28 gCm$^{-2}$yr$^{-1}$ respectively. Using these total C–CO$_2$ flux values and the root contribution to the SR flux (45%), we have obtained the estimates for HR from soils of the regions under study. The average value of HR for the steppe ecosystems of Tuva comprises 205±20 gCm$^{-2}$yr$^{-1}$. The same value for the steppe ecosystems of Khakassia is higher (282±27 gCm$^{-2}$yr$^{-1}$), which is logical due to more favorable climatic conditions in the regions. We have estimated heterotrophic respiration from soils of the natural steppe ecosystems in Tuva and Khakassia as 11.0±1.1 MtC per year and 3.9±0.4 MtC per year respectively.

According to our calculations with formula (2), the values of net ecosystem production for the natural steppe ecosystems in Tuva and Khakassia are positive and equal to 136±49 gCm$^{-2}$yr$^{-1}$ and 372±68 gCm$^{-2}$yr$^{-1}$ respectively. Thus, the natural steppe ecosystems in the regions under study are sink of atmospheric carbon. The estimations of productional and destructional fluxes in the steppe ecosystems of Tuva and Khakassia are shown in figure 3.

Our estimates for NEP in the steppe ecosystems are comparable with the values for similar flux in natural steppes (152±37 gCm$^{-2}$yr$^{-1}$) and abandoned agricultural lands (114–201 gCm$^{-2}$yr$^{-1}$) of the steppe zone in Khakassia obtained by the direct observation using the eddy covariance method [28]. It should be noted that the obtained estimates of carbon sink in the steppe ecosystems exceeds the average value of C–CO$_2$ sink in the forest ecosystems of Russia (66±15 gCm$^{-2}$yr$^{-1}$ [29]). Therefore the natural steppe ecosystems in the regions under study have a high carbon sink intensity. The total absorption of carbon dioxide in the steppe regions of Tuva and Khakassia can be evaluated as 7.3±2.7 MtCyr$^{-1}$ and 5.1±0.9 MtCyr$^{-1}$ respectively.

![Figure 3](image-url)

**Figure 3.** Estimations of heterotrophic soil respiration (HR), net primary production (NPP) and net ecosystem production (NEP) for the natural steppe ecosystems in Tuva and Khakassia Republics.

4. **Conclusions**

The natural steppe ecosystems occupy about 30% area in Tuva and Khakassia, where meadow, true, dry, and desert steppes are located. The average value of net primary production for the steppe
ecosystems under study amounts to $405\pm41 \text{ gCm}^{-2}\text{yr}^{-1}$. The annual absorption of carbon dioxide by vegetation is evaluated as $16.4\pm1.9 \text{ Mt C-CO}_2$ for these steppe regions. According to our calculation, the intensity of heterotrophic soil respiration in the steppe ecosystems is $221\pm17 \text{ gCm}^{-2}\text{yr}^{-1}$. Thus, the natural steppe ecosystems of the studied regions emit $9.6\pm0.9 \text{ Mt C-CO}_2$ per year into the atmosphere by means heterotrophic soil respiration. According to our estimation, the steppe ecosystems in Tuva and Khakassia are a significant sink of carbon dioxide from the atmosphere. The intensity of this carbon flux in the regions under study can be estimated as $184\pm41 \text{ gCm}^{-2}\text{yr}^{-1}$. The total absorption of carbon dioxide in the natural steppe ecosystems of Tuva and Khakassia is evaluated as $6.9\pm2.2 \text{ Mt C-CO}_2$ per year.

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